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Preface

This volume, which constitutes the forty-first in the series of annual TRANSACTIONS of the American Institute of Electrical Engineers, is the first to be published in the present sized pages, corresponding to the size of the Institute monthly JOURNAL. The change in size has been adopted chiefly for economic reasons; otherwise, the makeup of this volume does not differ materially from that of the preceding volumes. It is composed of papers, discussions, reports, etc., presented at the meetings of the Institute held during the year 1922. The TRANSACTIONS contains, therefore, no material which has not previously appeared in the JOURNAL. It is designed to be used principally as a book of reference for electrical engineers and its contents have therefore been selected by the Publication Committee to include only such material as will prove of permanent usefulness and interest to engineers. The arrangement of the contents is chronological, and each paper or group of papers is followed directly by the discussion thereon. The contents are conveniently indexed by title and author's name, affording ample facilities for ready reference. The material appearing in the monthly JOURNALS which is not included in this volume consists mainly of news of Institute activities and various contributed articles. The most important of these articles, however, are made available for reference by means of a supplementary index referring to the issues of the JOURNAL in which they are published. The synoptical and topical indexes have been omitted from this volume, and it is believed that they are less necessary than heretofore, because most of the principal articles are prefaced with a "Review of the Subject," giving a very complete synopsis of the article. A small table of contents is also included at the head of many articles, giving the title of each subdivision of the article, as well as the number of words under each subdivision. The A. I. E. E. Standards have usually been published in previous volumes of Transactions, but have been omitted from this volume as the frequent additions to the Standards have made them so voluminous that they now comprise a volume of considerable size by themselves. It is also considered that the publication of the Standards in the TRANSACTIONS was merely for a historical record and not for current reference. As the periodic revision of the Standards generally follows the publication of the TRANSACTIONS closely, the standards contained therein are obsolete nearly as soon as published and are of little value for reference purposes. This volume also contains the annual report of the Board of Directors for the fiscal year ending April 30, 1922 and lists of the officers and committeemen for the current year.

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Key West–Havana Submarine Telephone Cable System

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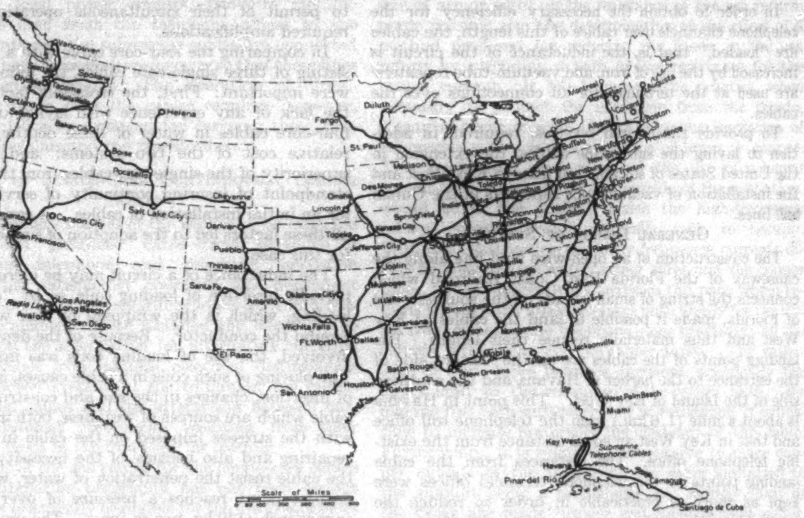
The system discussed in this paper includes three single-core continuously loaded submarine cables, each of which provides, in addition to a telephone channel, direct-current and carrier-current duplex telegraph channels. A description is given of the design and construction of the cables, of the method of superposing the various channels on each cable and of the terminal apparatus used for their operation.

On April 11, 1921, commercial telephone service was inaugurated between the United States and Cuba over three submarine cables laid across the Florida Straits between Key West, Florida and Havana, Cuba. These submarine cables are the longest and most deeply submerged which are in use for telephonic communication. They are from 100.2 to 104.9 nautical miles (186 to 195 km.) in length and are laid in water which for a part of the route is about 1000 fathoms (1830 m.) in depth.


Vancouver
Seattle
Olympia
Spokane
Tacoma
Walla Walla
Portland
Salem
Helena
Baker City
Boise
Pocatello
Duluth
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St. Paul
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Grand Rapids
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Cincinnati
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Louisville
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Kansas City
Topeka
Jefferson City
St. Louis
Cheyenne
Salt Lake City
Sacramento
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San Francisco
Denver
Pueblo
Trinidad
Santa Fe
Amarillo
Oklahoma City
Joplin
Muskogee
Little Rock
Memphis
Nashville
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Columbia
Denmark
Atlanta
Birmingham
Montgomery
Jackson
Mobile
Tallahassee
Jacksonville
Texarkana
Wichita Falls
Ft. Worth
Dallas
El Paso
Baton Rouge
New Orleans
Austin
Houston
Galveston
San Antonio
Radio Link
Los Angeles
Long Beach
Avalon
San Diego
West Palm Beach
Miami
Key West
Submarine Telephone Cables
Havana
Pinar del Rio
Camaguey
Santiago de Cuba
Scale of Miles
0 50 100 200 300 400 500

FIG. 1—MAP SHOWING THE SUBMARINE CABLES AND SOME OF THE IMPORTANT TOLL ROUTES IN THE UNITED STATES AND CUBA

The location of these cables and some of the important toll lines in the United States and Cuba are shown in Fig. 1. The cables were installed by the Cuban-American Telephone and Telegraph Company, an organization formed in 1919 by the American Telephone and Telegraph Company and the Cuban Telephone Company, for the purpose of providing telephone facilities between the United States and Cuba which would be suitable for connecting the telephone toll lines in the two countries.

The design of the submarine cables and the associated terminal equipment differs from previous systems because of the service which is furnished, the depth of water in which the cables are laid, and the length of the cables. The general features of this system will be indicated by the following summary of the requirements and the means which have been employed to meet them.

To give the service desired over these cables, it was necessary that the telephone channels be suitable for use in circuits connecting points in the United States, such as New York and Chicago, 1557 and 2453 miles (2510 and 3940 km.) distant from Key West, with Havana and other points in Cuba, which is about

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Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

700 miles (1126 km.) in length. It was required also that the cables furnish, simultaneously with the telephone, a number of telegraph channels. These are provided partly by direct-current channels and partly by carrier-current channels[1] using frequencies above the telephone range.

Because of the depth of water and other conditions, the cables are of the single-core type, generally used for deep sea submarine telegraphy in which the return path of the circuit is through the sea. An important modification of this type has been made for these cables in order to make the circuits more suitable for telephone and carrier use. This consists in surrounding the insulation of the central conductor with a wrapping of copper tapes forming an uninsulated return conductor.

In order to obtain the necessary efficiency for the telephone channels over cables of this length, the cables are "loaded," that is, the inductance of the circuit is increased by the use of iron, and vacuum-tube repeaters[2] are used at the terminals for all connections over the cables.

To provide the desired services, required, in addition to laying the submarine cables, the extension in the United States of suitable toll lines to Key West and the installation of vacuum-tube repeaters in the Cuban toll lines.

General Design of System

The construction of an open-wire land line along the causeway of the Florida East Coast Railroad which connects the string of small islands off the southern end of Florida, made it possible to land the cables at Key West and thus materially reduce their length. The landing points of the cables are on the western side of the entrance to the harbor of Havana and the southern side of the Island of Key West. This point in Havana is about a mile (1.6 km.) from the telephone toll office and that in Key West an equal distance from the existing telephone office. The distances from the cable landing points to the telephone terminal offices were kept as short as practicable in order to reduce the possibilities of interference from power circuits.

The water in the Florida Straits, starting from Key West, increases gradually in depth. Five miles (9.3 km.) from shore it is about 40 feet (12.2 m.) deep, at 15 miles (27.8 km.) about 700 feet (214 m.), and at 35 miles (65 km.) about 3000 feet. (915 m.) From that point on to within about three miles (5.6 km.) of Havana it is from 3000 feet (915 m.) to 6000 feet (1830 m.) in depth, being about a mile (1.86 km.) deep within five miles (9.3 km.) of Havana. These depths of water eliminated from consideration the use of a paper-insulated cable such as is commonly employed for telephone purposes on land or in shallow water. The most suitable construction for great depths is the submarine telegraph type of cable with an insulation of gutta-percha or similar material

Previous gutta-percha or rubber-insulated submarine telephone cables have, in general, contained four cores arranged to provide three and sometimes four telephone circuits. Two of these circuits, the "physicals," have been obtained directly from the two pairs of wires, one superposed circuit, the "phantom," has been obtained from the two wires of each pair in parallel and in some cases a second superposed circuit has been formed by the four wires in parallel with a sea return. There was considerable question, however, in this case, whether a cable of this type could be sufficiently well balanced to keep the cross-talk between the two superposed circuits and the physical circuits low enough to permit of their simultaneous operation with the required amplifications.

In comparing the four-core cable with a system consisting of three single-core cables, the following factors were important: First, the cross-talk factor; second, the lack of any experience with laying and repairing four-core cables in water of these depths; third, the relative cost of the two systems; and fourth, the superiority of the single-core cables from the important standpoint of insuring continuity of service, at least for an initial installation of cables. A consideration of all these factors led to the adoption of single-core cables for this case.

The inductance of a circuit may be increased by the periodic insertion of loading coils, or by "continuous" loading, which is the wrapping of iron wire or tape around the conductor. Because of the depths of water involved, the use of loading coils was impracticable. The placing of such coils in a cable causes, at the points of insertion, changes in the size and construction of the cable which are sources of weakness, both in connection with the stresses imposed on the cable in laying and repairing and also because of the necessity of making the cable resist the penetration of water, which at the deepest point reaches a pressure of over a ton per square inch (140 kg. per sq. cm.). The use of continuous loading for these conditions is advantageous not only mechanically in that it gives a uniform structure but also from the standpoint of keeping the terminal impedance of the cable uniform over the range of frequencies to be used. In repairing a coil-loaded cable in deep water it is practically impossible to maintain the regular spacing of the coils which is necessary for this uniformity of impedance. This uniformity is important in obtaining the close balance between the impedance of the cable and that of a network of impedance elements which is required for the two-way operation of amplifiers on the circuit.

These cables were planned to provide New York-Havana connections for which a transmission equivalent of under fifteen miles of standard cable (cable having resistance of 88 ohms and capacity of 0.054 microfarad per loop mile) was desired. Since the operating equivalent of the New York-Key West portion of the circuit is about ten miles, the sum of the amplifications applied at the terminals of the cable must be within five miles of its equivalent. It was estimated that practicable cables could be obtained which would have transmission equivalents of about 25 miles of standard cable. This required that the amplifications at the terminals should average about ten miles. As the interference produced on such a cable by power systems, by other communication systems, and by natural disturbances and the cross-talk between the cables themselves are amplified also, the requirements for these factors were correspondingly more exacting.

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[1] Colpitts and Blackwell, "Carrier Current Telephony and Telegraphy" Journal A. I. E. E., April, May and June, 1921.

[2] Gherardi and Jewett, "Telephone Repeaters" A. I. E. E. Trans., pp. 1287 to 1345, 1919.

To reduce the interference at the terminals of the cables from local power circuits, two-wire metallic circuits are used from the telephone offices to the landing points and the submarine cables are connected to the land lines through transformers so that these lines are balanced to ground. The operation of direct-current telegraph over the cables requires, however, that connections be arranged for carrying these telegraph channels around the transformers.

OPERATION OF SINGLE-CORE CONTINUOUSLY LOADED CABLES

The preliminary studies of the results to be expected with a loaded "grounded" cable circuit arranged for simultaneous telephone and telegraph operation indicated that satisfactory operation was dependent upon a number of factors regarding which little information was available. These included the effect of the sea return on the attenuation for alternating currents, the interference from natural electrical disturbances and from power systems at the terminals, the induction between cables and the interaction between currents of different frequencies resulting from their superposed fields in the iron used for loading.[3]

The effect of the sea return for the single-core cables used for submarine telegraphy has not been serious because it is practically negligible for the low frequencies involved. For direct currents, the cross-section of the return path is very large and its resistance low, even though the specific resistance of sea water is relatively high, of the order of ten million times as great as that of copper. For alternating currents, however, the return currents crowd in near the cable and the resistance of the return path is higher. This crowding effect of the return currents increases with frequency and consequently the resistance of the return path becomes greater. For frequencies in and above the telephone range the return currents are forced into the steel armor wires around the cable and into the layer of water just outside of the insulation. The small effective cross-section of the water involved and the losses in the armor wires cause the resistance of the return path to become a large part of the total resistance of the circuit and thus to have a large influence on the attenuation. The results of a few measurements of the sea return resistance for telephone frequencies, which had been made by British and French engineers, were published[4] in 1913 in an article discussing the factors involved in the use of single-core cables for telephony.

In connection with the plans for the Key West-Havana cables, a theoretical investigation[5] was made to determine how the resistance of the sea return is affected by the dimensions and construction of the cables and how it varies with frequency. This work in addition to giving a basis for investigating the effect of the dimensions of the cable and of the number and size of armor wires on the resistance of the sea return, made possible also the determination of the effect of a method proposed for reducing the losses in the sea return by providing a path of low resistance for the return current. It has long been the practise, when necessary to protect the insulation from the teredo, a marine borer, to wrap the gutta-percha insulation of submarine cables with a thin tape of brass or copper. This conducting tape suggested the use of a heavy copper tape, which, being just outside of the insulation, would be in the position which the high-frequency return currents would naturally seek to occupy. With this construction the lower frequency currents divide between the sea water, armor wires and the copper tapes, but as the frequency increases the part which returns through the tapes increases until finally for the upper frequencies in the telephone range practically all the current returns through the copper tapes. The resistance of these tapes becomes, therefore, practically the upper limit to the resistance of the return path. By making this path sufficiently low in resistance, it is possible to increase materially the efficiency of the cable. Furthermore, it is relatively inexpensive to place copper outside of the insulation, the main limitation to the amount being a mechanical one; namely, that as the tapes are made heavier and consequently stiffer, there is danger of damaging the insulation when the cable is bent. It was found that this idea of providing a conductive tape for the return was not new,[6] but investigation failed to show that it had ever been used or that any quantitative information had been published as to its effectiveness. This construction forms practically a concentric cable in which the outside cylinder is in contact with the water. In addition to its beneficial effect on the sea return, it is desirable also in that by reducing the external field of the circuit it decreases the induction between adjacent cables and also tends to decrease the effect of extraneous electrical disturbances.

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[3] Fondiller and Martin, "Hysteresis Effects of Varying Superposed Magnetizing Forces" JOURNAL A. I. E. E., February, 1921.

[4] Devaux-Charbonnel, *Journal Telegraphique*, May 25 and June 25, 1913.

[5] Carson and Gilbert, "Transmission Characteristics of the Submarine Cable." *Journal of the Franklin Institute*, December 1921.

[6] British Patent No. 10,313 of 1895, Willoughby Smith and W. P. Granville.

In order to get directly experimental information regarding the interference and the effect of the sea return on submarine cables, permission was obtained from the British Columbia Telephone Company to make tests on their cable to the island of Vancouver,[7] from the Western Union Telegraph Company to test their cables landing at Key West from Cuba, and from the United States Government to make measurements on a cable from Key West to Sand Key, a small island about 8 miles (14.8 km.) from Key West on which are located a lighthouse and a weather bureau station.

The Vancouver cable is a four-core continuously loaded gutta-percha cable with a brass protective tape wound around the group of cores. Measurements were made of the sea return for grounded circuits, of the interference on grounded circuits and of the induction from a telegraph cable of the Canadian Pacific Railroad which parallels the telephone cable. In addition, tests were made to get some indication of the cross-talk which might be expected between the physical and superposed circuits in such a cable and of the regularity of the impedance in a continuously loaded cable. Tests were also made of the interaction between currents of telegraph and telephone frequencies. The superposition in the iron wire loading of the fields of these two currents has been found[8] to increase the attenuation of the circuit for telephone currents. This has been called the "flutter" effect.

The Western Union cables are single-core gutta-percha-insulated non-loaded cables with protective metal tapes. Measurements were made of the interference on the cables and also of the cross-talk between the cables.

The Sand Key cable is a four-core non-loaded rubber-insulated telephone cable which has no protective metal tape. On this cable the sea return effect and the interference were measured.

It should be noted that measurements cannot be made directly of the sea return resistance for telephone frequencies. The resistance of the grounded circuits was determined from measurements of the impedance of the circuit, from measurements of the attenuation and from such data regarding the constants of the cables as could be obtained from tests on short pieces. The resistance of the conductor itself was obtained from tests on metallic circuits. For the Vancouver cable, this included the effect of the loading on the resistance of the circuit for alternating currents.

The magnitude of the sea return effect so determined checked closely the theoretical computations. In the case of the Vancouver cable this check involved taking into account the thin protective brass tape which had an appreciable effect. It was found also that the interference both from natural sources and from power systems would not be serious with amplifications even larger than those required on the Key West-Havana telephone cables. The tests for cross-talk between the cables at Vancouver which were about a mile (1.86 km.) apart for their length of about thirty miles (55.6 km.) gave no indication of induction from one cable to the other. The test on the Western Union cables which all terminated in the same hut at Key West gave a maximum cross-talk of less than 10 units at 1000 cycles (a unit of cross-talk being a ratio of current in the disturbed circuit to current in the disturbing circuit of 1 to 1,000,000). The flutter tests on the Vancouver cables showed that if the currents of the several channels were kept within reasonable limits, this effect should not cause trouble even for longer cables.

The results of these tests removed any question of serious interference and cross-talk with single-core cables under the proposed conditions. They verified the serious effects of the sea return resistance, but by providing a check on the theoretical work, gave assurance that this could be applied in estimating the effect of employing heavy copper tapes to limit the resistance of the sea return.

CABLE DESIGN

Conductor. To provide flexibility and security against breakage, it is customary to make the central conductor of a submarine cable not of a single solid wire but of a central wire surrounded either by a layer of copper wires or by a layer of thin copper tapes. In the present case the latter construction was used because of the smoother surface it provides for the loading wires. It also tends to give somewhat lower resistance and capacity for a given weight of copper. The actual conductor consists of a round copper wire 0.115 inch (2.92 mm.) in diameter surrounded by five copper tapes each 0.077 inch (1.96 mm.) wide and 0.0125 inch (0.32 mm.) thick. This conductor has a weight of 350 lb. (159 kg.) per nautical mile (1.86 km.). It was specified to have a resistance not to exceed 3.52 ohms per nautical mile at 75 deg. fahr. (24 deg. cent.)

Loading. The cable is loaded with a single close layer of iron wire 0.008 inch (0.2 mm.) in diameter applied directly upon the central copper conductor. There are approximately 120 turns of this loading wire per inch length of the conductor. While an equally efficient cable for the transmission of telephone frequencies could have been produced at a lower cost by using a smaller conductor with heavier loading in the form of more layers or thicker iron wire or both, the requirements of the carrier telegraph made the lighter loading more desirable, as will be shown later.

Insulation. The loaded conductor is treated with Chatterton's compound and insulated with gutta-percha mixture applied in three layers, thus forming a

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[7] La Belle and Crim, "The Gulf of Georgia Submarine Telephone Cable." A. I. E. E. TRANS., 1913.

[8] Fondiller and Martin, loc. cit.

"core." The amount of this insulating material is 315 lb. (143 kg.) per nautical mile which provides a wall thickness of approximately 0.135 inch (3.4 mm.). Because of the loading and the high frequencies for which the cable is used, low alternating-current conductance was specified for the dielectric, requiring the use of a special gutta-percha mixture.

Return Conductor. As already stated copper tapes were applied to the outside of the core to diminish the losses caused by the sea return. In the actual construction a copper tape 1 inch (2.54 cm.) wide and 0.004 inch (0.1 mm.) thick is applied directly upon the core with short enough lay to provide safe overlap. Upon this tape are laid two heavier copper tapes, each 0.625 inch (1.59 cm.) wide and 0.022 in. (0.56 mm.) thick. These two heavier tapes are applied with a much longer lay, and are laid side by side with the edges not quite touching. The entire system of copper tapes, weighing approximately 850 pounds (390 kg.) per nautical mile, provides a return conductor with a direct-current resistance in the laid cables of approximately 1.65 ohms per nautical mile. The thin tape first applied directly on the core furnishes also the protection against injury of the core by the teredo.

Sea Grounds. The main core with loaded central conductor and uninsulated return conductor, as described above, extends through the entire length of cable. In submarine telegraph cables it is the practise, in cases where it is especially important to reduce as much as possible all disturbances from outside sources, to construct portions of the cable near the ends with two cores so that the return part of the circuit is carried some distance out to sea before being connected to ground. In accordance with this practise, portions of each end of these cables were made with such two-core construction. In these portions the return or sea ground core has the same central conductor as the main core, no loading iron, the same amount of insulating material per unit length, and the thin protective copper tape but no heavy copper tapes. At the outer end of each of these sea ground cores its conductor is connected by electric welding to the conductive copper tape on the main core.

Armoring. The armoring protects the core and gives tensile strength to the cable to permit its being handled for laying and for subsequent lifting in case of repairs. As is usual, the size and number of armor wires are adapted to the location, taking into account such matters as depth, nature of bottom and water currents. The shore end portions, where because of relatively shallow water the cable is most likely to be injured, have the heaviest armor wire, which in this case has a diameter of 0.3 inch (7.6 mm.). The portions of the cable lying in the deepest water are armored with wire having a diameter of 0.104 inch (2.6 mm.). Intermediate portions of the cable have armor wires whose diameter is 0.192 inch (4.9 mm.). The 0.104 inch armor wire for the deep sea cable is a springy steel wire intended to give great tensile strength to the cable, while the heavier armor wire for the shore end and intermediate cable in shallower water consists of soft iron. The armor wire in all types of the cable is galvanized and is coated with preservative compound before being applied to the cable. The wires for the deep sea portions, in addition to being compounded, are individually wrapped with an impregnated fabric tape, which serves the double purpose of protecting the wire and making the cable more flexible by keeping the armor wires separated.

Before the armor wires are applied, the core or cores are served with tanned jute yarn applied in one or more layers to form a bedding for the armor wires. In those portions of the shore end cable which have two cores, these are laid up together with a relatively long lay and with tanned jute in the interstices between the two cores, before applying the jute bedding for the armor wire.

TABLE I
LENGTHS OF THE SEVERAL TYPES IN EACH CABLE

Type of Cable	Armoring or Sheathing	Length—Nautical Miles*		
		Western Cable	Center Cable	Eastern Cable
	Key West End			
Shore end twin with lead-covered cores...	17 No. 1 (0.300 inch) wires	0.2	0.2	0.2
Shore end twin plain cores...............	15 No. 1 (0.300 inch) wires	3.0	3.0	3.0
Shore end single.......	10 No. 1 (0.300 inch) wires	14.0	9.5	10.5
Intermediate single....	14 Nos. 6 (0.192 inch) wires	10.5	10.5	9.5
Deep sea single.........	20 No. 12 (0.104 inch) wires (taped)	73.3	74.5	79.2
Intermediate single....	14 No. 6 (0.192 inch) wires	1.5	1.0	1.0
Shore end twin plain cores...............	15 No. 1 (0.300 inch) wires	1.8	1.3	1.3
Shore end twin with lead-covered cores...	17 No. 1 (0.300 inch) wires	0.2	0.2	0.2
	Havana End			
Total................		104.5	100.2	104.9

*A nautical mile is 6087 feet (1855 meters).

The total length of cable laid on each of the three routes as given is somewhat greater than the distance along the route in order to provide slack.

In the extreme shore ends a short length is made with each core covered with a close fitting tube of lead to protect it from light and air, which would tend to cause deterioration of the gutta-percha in those portions which may extend out of the water.

The lengths of the several types differ somewhat in the three cables because of differences in the routes. In a general way the heaviest type of armoring extends from the shore to a point where the depth is approximately 100 fathoms (183 meters) and the intermediate type from this point to one where the depth is approximately 250 or 300 fathoms (457 to 549 meters), with the deep sea type in all the deeper parts. This arrangement carries the heavily armored cable much farther out from the Key West end than from the Havana end because of the much more gradual increase of depth of water at the Key West end. For the same reason the two-core or twin cable, which provides the return core for the sea ground, is carried out considerably farther at the Key West end. The approximate length of each type actually installed and the sequence of types are given for each cable in Table I.

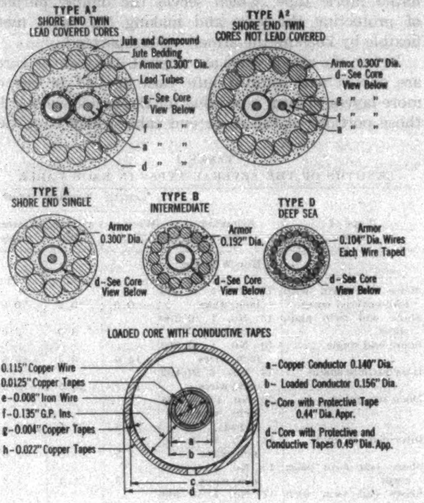
TYPE A²
SHORE END TWIN
LEAD COVERED CORES
Jute and Compound
Jute Bedding
Armor 0.300" Dia.
Lead Tubes
g-See Core View Below
f " "
a " "
d " "
TYPE A²
SHORE END TWIN
CORES NOT LEAD COVERED
Armor 0.300" Dia.
d-See Core View Below
g " "
f " "
a " "
TYPE A
SHORE END SINGLE
Armor 0.300" Dia.
d-See Core View Below
TYPE B
INTERMEDIATE
Armor 0.192" Dia.
d-See Core View Below
TYPE D
DEEP SEA
Armor 0.104" Dia. Wires Each Wire Taped
d-See Core View Below
LOADED CORE WITH CONDUCTIVE TAPES
0.115" Copper Wire
0.0125" Copper Tapes
e-0.008" Iron Wire
f-0.135" G.P. Ins.
g-0.004" Copper Tapes
h-0.022" Copper Tapes
a-Copper Conductor 0.140" Dia.
b- Loaded Conductor 0.156" Dia.
c-Core with Protective Tape 0.44" Dia. Appr.
d-Core with Protective and Conductive Tapes 0.49" Dia. App.
a
b
c
d

Fig. 2—Cross-Sections of the Various Types of Cable Used

Some of the principal details of the design of the several types of cable with their relative dimensions are shown in the diagrams of Fig. 2. A photograph of specimens showing the appearance of the cables and some details of their construction is reproduced in Fig. 3. The over-all diameter of the largest shore end cable is approximately 2.4 inches (6.1 cm.) and that of the deep sea type approximately 1.2 inch (3.0 cm.).

Cable Manufacture and Testing

The cables were manufactured and laid by the Telegraph Construction and Maintenance Company, Limited, of London.

Since the mechanical structure of these cables is in most respects similar to that of gutta-percha-insulated submarine telegraph cables, the manufacture was in the main carried on along the lines followed in making such cables. Briefly, this process is as follows: The central conductor is made by stranding around a copper wire a layer of finer copper wires or a layer of thin copper tapes. This conductor is then covered with the gutta-percha insulating material, generally applied in two or three layers to diminish the chance of a defect extending through the insulating envelope. Before applying the gutta-percha, the conductor is treated with a thin coating of Chatterton's compound, to fill the interstices in the conductor and to increase the adhesion between the conductor and the gutta-percha. The insulated conductor so formed is known as a "core" and is manufactured in lengths generally ranging from 1½ to 3 nautical miles (2.8 to 5.6 km.), depending upon the weight of the core. In general it is necessary to manufacture heavy core in shorter lengths than light core. After the necessary inspection and tests the core lengths are served with tanned jute yarn, in one or more layers to form a bedding for the armor wires. In case the cable is to be protected against the teredo, the core, before being served with the jute bedding, is covered with a close overlapping layer of metal tape (generally brass). Either before or after being served with the jute bedding, the individual cores are joined together to form longer lengths. They then pass to the armoring or closing machine, which applies the armor wires. The galvanized armor wires, before being used, are coated with preservative compound and the armoring machine applies over the outside of the armor wires wrappings of tarred jute yarn or of a heavy burlap-like fabric known as "Hessian" band. Between the armor wires and these outer wrappings, as well as between and over the several wrappings, coatings of preservative compound are applied. From the armoring machine the cable is laid directly into the factory cable tanks, where it is treated with whitewash to prevent sticking, and where it is then kept submerged in water until it is transferred to similar tanks in the cable ship, for transport and laying.

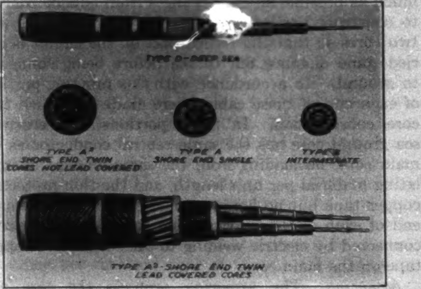
TYPE D—DEEP SEA
TYPE A² SHORE END TWIN CORES NOT LEAD COVERED
TYPE A SHORE END SINGLE
TYPE B INTERMEDIATE
TYPE A²-SHORE END TWIN LEAD COVERED CORES

Fig. 3—Specimens of the Various Types of Cable Used

In the splicing of two lengths of cable, either at the factory or on the cable ship, a core joint is first made to unite the conductor and its insulation in the two portions of cable. Over this the jute bedding is then reapplied by hand, and finally the armor wires which had previously been opened up and laid aside, are laid back in such a way that the armor wire from one of the two pieces extends for a length of 15 feet (4.6 m.) or more over the armor wire of the other part. After laying the armor wire in place the splice is served with several tight bindings of galvanized iron wire and the whole covered by a continuous close binding of tarred yarn.

In the manufacture of these cables the application of the iron loading wire to the conductor added an operation which, because of its relative slowness, largely determined the length of time required for manufacture. The heavy conductive copper tapes which are applied to the outside of the core could, because of their weight, be handled only in limited lengths of something like 200 feet (61 m.). Successive portions of this tape were joined together by welds. A soldering or brazing operation would have required the insertion of a dissimilar metal, which would increase the tendency to electrolytic corrosion when in contact with sea water.

The cable in process of manufacture was subjected to the usual visual and manual inspections and electrical tests. The core was manufactured in individual lengths of approximately two nautical miles (3.7 km.) each. These individual core lengths, after 14 days' submersion in water, were tested at a temperature of 75 deg. fahr. for d-c. conductor resistance, insulation resistance and capacity. During the process of jute serving and armoring frequent electrical tests were made so that if any injury or fault should develop it could be detected and the defective part removed or repaired. Measurements of d-c. conductor resistance, insulation resistance and capacity were again made on the completed cable at various times during and after the manufacture, the loading upon shipboard and during the transport and laying of the cable.

In addition to these tests, which are customary for all gutta-percha-insulated submarine cables, additional measurements were made on the present cables. The inductance and capacity of each length of core were measured by alternating-current methods. A large number of short lengths of core selected so as to represent all parts of the cable were measured for capacity and conductance at 1000 cycles per second and at 75 deg. fahr. It was found that the capacity as measured by a direct-current galvanometer method agreed within one per cent with the capacity obtained by measurements with alternating current of 50 cycles or 1000 cycles per second. Table II gives the average values per nautical mile of the several electrical constants as measured on the cores at a temperature of 75 deg. fahr. 14 days after manufacture.

TABLE II

Direct-Current resistance	3.32 ohms
" " capacity	0.311 microfarads
" " insulation resistance after one minute electrification	920 megohms
1000-Cycle inductance	4.35 milhenrys
" " conductance	12.8 micromhos

The corresponding values for the completed cable when laid are in some respects materially different. The insulation resistance is higher in the laid cables because it increased both with age and with the lower temperature at the sea bottom. The 1000-cycle conductance decreased with age but increased with the lower temperature—these two effects thus tending to offset one another. The inductance for the completed cable corresponds to that of a central loaded conductor with a concentric cylindrical return circuit, while the inductance measured on the individual cores was that of a gutta-percha-insulated loaded conductor in bifilar form. The conductor resistance is, of course, different because of the lower temperature of the laid cables.

These extensive measurements were made to obtain data regarding the electrical properties of the cable and of the individual lengths of core. The data on the core lengths were used to determine their best sequence, in order to make the impedance at the ends of the cable as uniform as possible over the range of frequencies required for telephone transmission.

CABLE LAYING

The cable ship arrived at Key West February 7, 1921, and after certain preliminaries such as securing barges and tugs and making the necessary arrangements with the Government authorities proceeded with the laying operations.

Where the water was deep enough the cables were laid directly from the cable ship which brought them from the cable factory to the Florida Straits. In shallower water the cables were laid from a barge or lighter towed by a tug. The actual sequence of laying each cable was as follows: First a length of approximately 6 or 8 miles (11 or 15 km.) was laid from a barge at the Key West end. The barge with its length of cable was brought as near as possible to the Key West cable hut. The extreme Key West end of the cable was pulled from the barge to the shore, laid in a trench on the beach and terminated in the hut. To facilitate this landing, the portion between the barge and the hut was supported at intervals by empty casks, to which the cable was tied by ropes, and thus floated in the water. After the landing of the shore end, the main portion of this cable section remaining on the barge, its length having been suitably chosen, was laid outward to a point having a depth sufficient for the cable ship. At this point the end was sealed and dropped to the bottom with an anchor attached to a marking bouy. Later this cable end was picked up by the cable ship and spliced to the next length, which was then laid by the ship from this point to the end of the intermediate type of cable, which as already stated reached to a point where the depth of water was about 250 or 300 fathoms (457 or 549 meters). Again the end was sealed and laid overboard with an anchor and a marking bouy. Next a short length of shore end cable was laid by barge from the Havana cable hut outward and its end lifted to the ship and there spliced to the main length of cable, which was then laid by the ship from this point near Havana to the point where the bouy marked the location of the end of the intermediate cable previously dropped. After lifting this bouyed end the final splice was then made on the ship connecting the bouyed end to the main cable on the ship and the work of laying completed by dropping the final splice overboard.

After the completion of the laying of the three cables the final acceptance tests were made at the ends of the cables in the Key West cable hut. These tests covered only such measurements as are customary on submarine telegraph cables; *i. e.*, measurements of direct-current conductor resistance, direct-current insulation resistance and direct-current capacity. They were intended merely to determine these direct-current properties and to insure the electrical integrity of the cables after completion of the laying. The results of these tests are shown in Table III which gives values per nautical mile:

TABLE III

	Western Cable	Center Cable	Eastern Cable
Conductor resistance—ohms	3.13	3.11	3.11
Capacity-microfarads......	0.315	0.316	0.314
Insulation resistance after one minute electrification—meghoms..........	8900	7600	8500

These tests were completed the evening of February 25, 1921, and on February 26, 1921, the surplus and spare cable was delivered into the storage tank at Key West and the cables were formally accepted.

CABLE CHARACTERISTICS

In view of the fact that the return circuit of the single-core cable includes the sea water, the operation of the cables could not be determined accurately until they were laid. The lengths of the laid cables are such that determinations at telephone and carrier frequencies of the primary constants, resistance, inductance, capacity, and conductance can not be made directly. The secondary constants, the impedance and attenuation, can be measured and these data together with the results of the tests on short pieces used to estimate the primary constants.

After acceptance, extensive alternating-current measurements were made on the three cables, covering the range from about 100 to 6000 cycles. These tests included determinations of the ratio of the current received at one end of the cable to that sent in at the other and measurements of the impedance at each end of each cable with the far end closed through the characteristic impedance of the cable. From these measurements of the ratio of the "received" current I_2 to the "sent" current I_1, the attenuation constant α per nautical mile of each of the cables was obtained from the relation

$$e^{-L\alpha} = \frac{I_2}{I_1}$$

where L is the length in nautical miles. These values for a range of frequencies are given in Table IV. It is seen that the values for the three cables do not differ materially. The average of the attenuations for the three cables is shown also in Fig. 4.

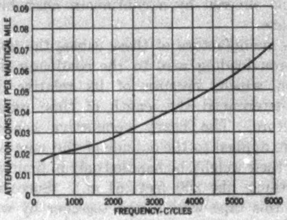

FIG. 4—AVERAGE ATTENUATION CONSTANT OF THE CABLES

The transmission equivalent of the center cable, which is the shortest, is shown in terms of miles of standard cable at 800 cycles (attenuation of one mile of standard cable at 800 cycles is 0.109) in Fig. 5. This figure gives in addition the combined equivalent of the compositing apparatus in the two huts and the land cables at the two ends between the cable huts and the offices, and also the total equivalent of the circuit from the Key West office to the Havana office.

Table V gives the total equivalent of the circuit over the center cable between the two offices and the corresponding current ratios.

The variation of the resistance and reactance components of the impedance of the cable is illustrated in Fig. 6. The deviations of these curves from those that would be obtained if the cable were absolutely uniform throughout its length are under 3 per cent.

From these measurements, from the tests in the factory and from computations, it is possible to estimate fairly closely the constants of the cables. The average of these constants for the three cables is given in Table VI. The conductance is not given for frequencies of 1000 cycles and lower as its effect for this range is so small as to make determination of its value practically impossible under the conditions.

TABLE IV

ATTENUATION CONSTANT PER NAUTICAL MILE

Frequency Cycles per sec.	Cables			
	Western	Center	Eastern	Average
200	0.0170	0.0165	0.0168	0.0168
500	0.0196	0.0197	0.0190	0.0194
1000	0.0216	0.0216	0.0216	0.0216
2000	0.0278	0.0278	0.0278	0.0278
3000	0.0357	0.0361	0.0371	0.0363
4000	0.0450	0.0460	0.0470	0.0460
5000	0.0558	0.0574	0.0594	0.0575
6000	0.0710	0.0716	0.0748	0.0725

Estimates were also made of the distribution of the resistance in the circuit for a range of frequencies.

TABLE V
TOTAL EQUIVALENT-HAVANA OFFICE TO KEY WEST OFFICE
CENTER CABLE

Frequency Cycles	Equivalent Miles Standard Cable 800 Cycles	Current Ratio
200	19.8	0.116
500	19.4	0.121
1000	20.8	0.104
2000	27.2	0.0516
3000	35.7	0.0204
4000	46.0	0.00664
5000	58.0	0.00180
6000	72.7	0.00036

The curves of Fig. 7 give average values for the three cables of the d-c. conductor resistance, the increase of the conductor resistance with frequency due to skin effect, the resistance of the sea return and the resistance added to the circuit by losses in the loading iron. The large part contributed by the loading at the higher frequencies shows why it is desirable to use the light loading where carrier frequencies are to be transmitted. The use of iron wire 0.012 inch in diameter would have increased the resistance added by the loading by about 55 and 90 per cent at 3000 and 5000 cycles respectively above the values obtained with 0.008-inch wire. These increases in resistance, in spite of the increase in inductance resulting from this change, would have increased the attenuation by 33 and 65 per cent at these frequencies.

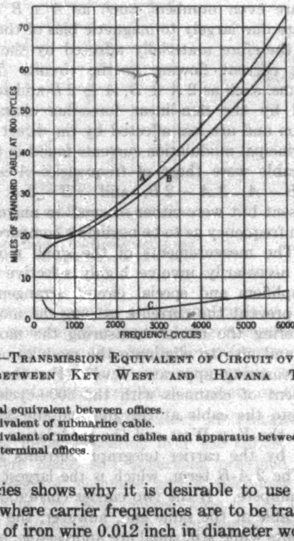

FIG. 5—TRANSMISSION EQUIVALENT OF CIRCUIT OVER CENTER CABLE BETWEEN KEY WEST AND HAVANA TELEPHONE OFFICES

A. Total equivalent between offices.
B. Equivalent of submarine cable.
C. Equivalent of underground cables and apparatus between submarine cables and terminal offices.

TABLE VI
AVERAGE ELECTRICAL CONSTANTS OF CABLES PER NAUTICAL MILE

	Frequency-Cycles per Second								
	0	200	500	1000	2000	3000	4000	5000	6000
Resistance-ohms	3.12	4.1	4.5	4.8	5.8	7.2	8.7	10.9	13.7
Conductance-micromhos	..	..	..	..	45	90	140	180	230

Capacity—0.31 microfarad
Inductance—0.0041 henry
Effective Permeability of Loading—115

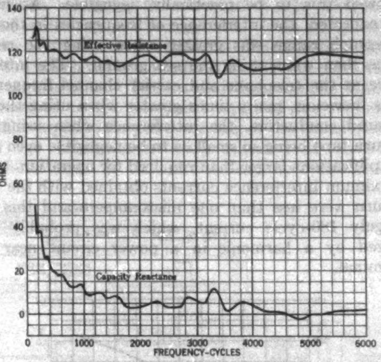

FIG. 6—IMPEDANCE OF EASTERN CABLE AS MEASURED FROM THE KEY WEST TERMINAL

Estimates of the resistance of the sea return which would have been obtained in the deep sea portion of the cable if no copper tapes had been provided give values of 4, 6.5 and 8 ohms per nautical mile at 1000, 3000 and 5000 cycles. The resistance actually obtained with the copper tapes does not exceed 1.7 ohms at 5000 cycles, as shown on the curves of Fig. 7. The greater values would have increased the attenuation by approximately 30 per cent at 1000 cycles and by 50 per cent at the two higher frequencies.

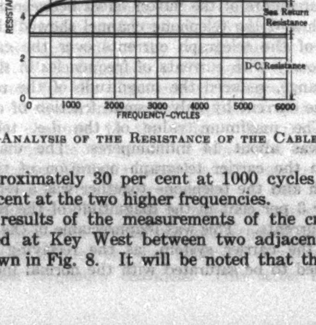

FIG. 7—ANALYSIS OF THE RESISTANCE OF THE CABLE CIRCUIT

The results of the measurements of the cross-talk obtained at Key West between two adjacent cables are shown in Fig. 8. It will be noted that the cross-talk between the cables when the connection is made to the copper tapes is less than one per cent of that obtained when the connection is made to the insulated sea ground conductors.

Measurements of the interference on these cables showed this to be practically negligible. As might be expected, the interference of frequencies in the d-c. telegraph range was greater when using the return tape than when using the sea ground. The interference at the telephone and carrier channel frequencies was, however, many times greater when using the sea ground conductors, the interference when using the return tape being so small as to be negligible even with amplifications larger than required for operation. The maximum interference currents obtained with the tape return were less than one microampere and this was largely 180-cycle current, which was probably produced by a harmonic in a power circuit near the terminal.

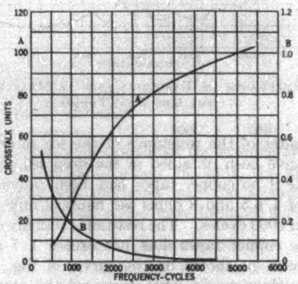

FIG. 8—CROSS-TALK BETWEEN TWO OF THE CABLES

A. Both cables using sea ground.

B. Both cables using copper tape return.

The results of the cross-talk and interference tests confirm the expected operation of the heavy copper tape return, that is, that practically all the current of frequencies in the important part of the telephone range and above would return through the tape. On the same basis the tape acts as a very effective screen against interference currents of these frequencies.

Measurements of the flutter effect between the d-c. telegraph and the telephone channel showed that the passing of the telegraph currents over the cable simultaneously with currents of frequencies in the telephone range, reduced the magnitude of the received telephone current by only a small fraction of one per cent. The maximum value of the d-c. telegraph pulses was about 14 milliamperes. The maximum effect on the carrier telegraph operation of the d-c. telegraph and the telephone together was a reduction of under 3 per cent in the magnitude of the received carrier currents. This was inappreciable in the operation of the carrier system, as the receiving circuit is designed to be saturated with the normal incoming current, so that slight changes in the sent currents or changes in the circuit efficiency have no effect on its output.

Investigation was also made of "modulation" effects in the loading. Where two currents of different frequencies, A and B, are superposed on the circuit and hence have their fields superposed in the iron wire loading, currents of other frequencies are set up in the cable as a result of the non-linear characteristics of the iron. The frequencies of these modulation currents are the sums and differences of the frequencies A and B and of their various harmonics, such as $A \pm B$, $2A \pm 2B$, $2A \pm B$, $A \pm 2B$, $3A \pm 3B$, $3A \pm 2B$, $3A \pm B$, $A \pm 3B$, and so on. The superposition of additional currents of frequencies different from A and B produces of course additional resultant modulation currents.

The even order modulation currents, that is, those of frequencies for which the sums of the coefficients of A and B are even numbers, such as $A \pm B$ and $2A \pm 2B$, are due largely to magnetic bias of the loading and are therefore materially affected by the amount of direct current flowing in the circuit. The odd order terms, such as $2A \pm B$, $A \pm 2B$ and so on, are produced by the non-linear force-flux characteristic of the iron and are less affected by the direct current.

The principal modulation currents found in the work on the cable were those of frequencies $A \pm B$, $2A - B$, $2B - A$, $3A - 2B$, and $3B - 2A$. Others were present but were either so small in magnitude or so high in frequency as to be negligible compared to the above. The measurements of the small modulation currents necessarily involve highly selective circuits, large amplifiers and special circuit arrangements in order to prevent the currents causing the modulation from entering the circuit measuring the modulation currents and also to eliminate the modulation effects in the measuring apparatus itself. For the present arrangement of channels with the 3000-cycle carrier flowing into the cable at Havana and the 3800-cycle carrier at the Key West end the modulation currents produced by the carrier telegraph currents are very small. The $2A$-B term, which is the largest, is only 0.2 microampere. If the two carrier currents are sent into the cable at the same end, however, the modulation currents while still small are appreciable, as shown in Table VII.

TABLE VII

MAGNITUDE OF CARRIER CURRENTS ENTERING SUBMARINE CABLE

A—3000 cyles, 13.6 milliamperes
B—3800 " 18.5 "

MODULATION CURRENTS FROM CABLE

Frequency	Microamperes
A − B, 800 cycles	0.3
A + B, 6800 "	less than 0.1
2A − B, 2200 "	4.7
2B − A, 4600 "	1.3
3A − 2B, 1400 "	1.3
3B − 2A, 5400 "	0.3

While for these arrangements the modulation effects were found to be so small as to cause no serious interference, they may under some conditions become large enough to require consideration, particularly in connection with increasing the number of carrier telegraph channels over the cables. In that case, these modulation currents affect the number of channels, the current levels and the frequencies which can be used. This effect appears not only as noise in the telephone but also as interference between carrier channels. As an illustration of the magnitudes which may be obtained, Fig. 9 shows the 2 *A-B* term for a constant *A* frequency of 2500 cycles with the *B* frequency varying from 3000 to 5000 cycles. The magnitudes of both *A* and *B* are 30 milliamperes into the submarine cable at the same end, the modulation currents being measured also at that end. It is seen that for the lower frequency values of 2 *A-B*, the magnitudes are comparable with those of components of the telephone currents on the cable.

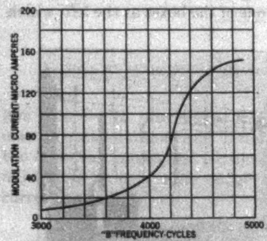

Fig. 9—Modulation Effect in Cables

Current of 2 *A*—*B* frequency for *A* frequency = 2500 cycles. Current of both *A* and *B* frequencies = 30 milliamperes into submarine cable.

Compositing Arrangement at Terminals

For the initial operation over the cables, arrangements were made and apparatus provided for two duplex telegraph channels and a telephone channel over each of the three cables. One of the telegraph channels is furnished by the direct-current system and the other by the carrier-current system using frequencies above the voice range. In addition to the above, a signaling channel required for the operation of the telephone channel uses currents of frequencies in the voice range. It is possible to employ this range since it is not required simultaneously for signaling and talking.

The general method of superposing these channels on the cable and connecting them to the terminal apparatus is shown in Fig. 10. As the channels are required to operate in both directions, the usual balance system is provided for each channel to prevent the currents sent out at one terminal from operating the receiving apparatus at that terminal. The balance system consists essentially of a "bridge transformer" and a network of impedance elements designed to simulate the impedance of the line for a range of frequencies. The bridge transformer is a transformer with three windings, from two of which accurately located center taps are brought out. This transformer is thus suitable for providing a Wheatstone bridge circuit in which the two windings having mid-point taps serve as ratio arms. The transmitting amplifier output is connected to the mid-point taps and the receiving amplifier input to the third winding of the transformer. With the balancing network adjusted to have an impedance equal to that of the line, the transmitting amplifier does not send current into the receiving amplifier.

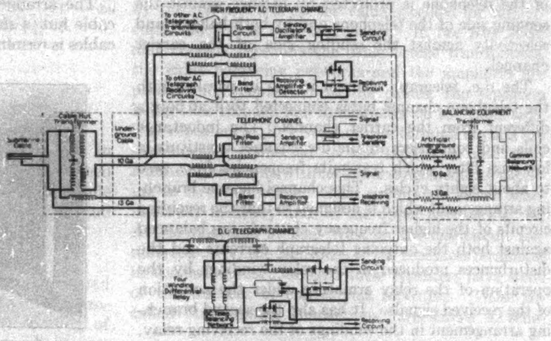
HIGH FREQUENCY A.C. TELEGRAPH CHANNEL
To other A.C. Telegraph Transmitting Circuits
Tuned Circuit
Sending Oscillator & Amplifier
Sending Circuit
To other A.C. Telegraph Receiving Circuits
Band Filter
Receiving Amplifier & Detector
Receiving Circuit
Cable Hut Transformer
Submarine Cable
Under-ground Cable
10 Ga.
13 Ga.
TELEPHONE CHANNEL
Low Pass Filter
Sending Amplifier
Signal
Telephone Sending
Band Filter
Receiving Amplifier
Signal
Telephone Receiving
BALANCING EQUIPMENT
Transformer
7:1
Artificial Underground Cable
Common Balancing Network
10 Ga.
13 Ga.
D.C. TELEGRAPH CHANNEL
Four winding Differential Relay
D.C. Telegraph Balancing Network
Sending Circuit
Receiving Circuit

Fig. 10—Compositing Arrangement at Terminals

Filters or selective circuits are placed in the sending circuits to insure that the outgoing currents of any channel do not contain frequencies which will interfere with the other channels, and in the receiving circuits to admit only those currents in the proper frequency range.

At the cable hut the submarine cable is connected by a 1 to 7 impedance ratio, specially balanced transformer to a two-wire underground cable circuit of No. 10 A. W. G. (diameter 0.102 inch, 2.6 mm.) conductors. Across the cable side of the transformer is bridged a No. 13 A. W. G. (diameter 0.072 inch. 1.8 mm.) two-wire circuit for the direct-current telegraph channel. The No. 10 circuit carries the telephone and the carrier telegraph channels to the office. The transformer serves to insulate the grounded submarine cable from the land cable and thus renders the latter less susceptible to interference from power systems. It also steps up the impedance of the cable to meet the impedance of the telephone and carrier channel terminal apparatus and aids in keeping the d-c. telegraph currents out of the higher frequency channels. This latter function is assisted by the condenser at the mid-point of the cable side of the transformer.

The telephone and carrier apparatus is connected in parallel to the No. 10 A. W. G. underground cable circuit. Each set of equipment contains a bridge transformer which separates the sending and receiving circuits. These two bridge transformers are connected in parallel both to the cable and to the common balancing network so that the sending circuit of either channel will not send current into the receiving circuit of the other channel. The sending channels are not so balanced against each other, but since each contains a filter or tuned circuit which presents high impedance to currents from the other sending circuit, little current flows from one sending circuit to the other. The receiving side of the telephone is protected by balance against the sending side of the telephone and by both balance and selectivity against the sending side of the carrier channel.

The d-c. telegraph channel is also in parallel with the telephone channel but is connected to it at points different from the carrier channel. The inductance coils and condensers in the d-c. channel constitute a low-pass filter which transmits frequencies from zero to about eighty cycles. This channel has one branching arrangement which is designed so that the receiving circuits of the higher frequency channels are balanced against both the outgoing telegraph currents and the disturbances produced in the relay windings by the operation of the relay armature under the actuation of the received signals. It has also the second branching arrangement in the windings of the receiving relay, to separate the sending and receiving telegraph circuits. This requires the second balancing network which is connected with this relay.

It will be noted that associated with the main balancing network shown in the right of Fig. 10 is a duplicate of all the apparatus and circuits between the terminal apparatus and the submarine cable. The balancing network itself is adjusted to simulate the impedance of the submarine cable over the range of frequencies required for the operation of the telephone and telegraph channels, particular attention being paid to have it meet this impedance for the range of the telephone channel. Because of the degree of uniformity obtained in the impedance of the cables, it was possible to get a very good simulation with a simple network of three impedance elements. If the cables had been less uniform it might have been necessary to employ a multi-section artificial cable such as is used with long submarine telegraph cables. The balancing transformer and artificial underground cable are adjusted to match the impedances of the corresponding elements in the cable circuit. By this means, it is possible to obtain a balance at the terminals of the bridge transformers which for any frequency in the telephone range is within 3 per cent of being perfect, thus making it possible to use high amplifications with this channel. The degree of balance is only slightly poorer in the carrier telegraph range.

Since the attenuation in the range available for carrier telegraph use is greater than that in the telephone range and the amplifications therefore necessarily larger, the land-line carrier telegraph practise was followed in not relying entirely upon the balance to prevent interference between the outgoing and incoming carrier currents but in using different frequencies in the two directions with the selective circuit and filter in the sending and receiving branches tuned respectively to these different frequencies. For operation from Havana to Key West a carrier frequency of 3000 cycles is used and for the opposite direction a carrier frequency of 3800 cycles.

The arrangement of the terminal apparatus in the cable hut is shown in Fig. 11. Each of the submarine cables is terminated in one of the boxes at the left, which are water-proof. The submarine cable enters the box from below, the two cores entering through separate bushings. The underground cable circuits from the office are brought into the boxes from above. Cables also lead from these boxes to the pots at the right which contain the transformers, condensers and inductance coils located at the hut. A tie cable enters all the boxes from below to make possible cross-connection of the circuits and apparatus.

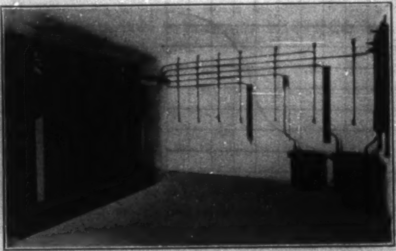

FIG. 11—APPARATUS IN CABLE HUT

TERMINAL EQUIPMENT

Amplifiers and signaling apparatus for the telephone circuits and terminal apparatus for the telegraph and carrier telegraph channels are provided for each cable at the terminal offices in Havana and Key West. Although these terminal units in general resemble those developed for similar uses on land-line telephone and telegraph circuits, they differ in many respects because of the high attenuation of the submarine cables and the different methods of operation required on these circuits.

The general theory and operation of telephone repeaters[9], carrier telegraph apparatus[10] and vacuum tubes[11] have been described in various publications. Those features in which the cable apparatus is similar to earlier types will not be discussed here in detail.

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[9] Gherardi and Jewett, loc. cit.

[10] Colpitts and Blackwell, loc. cit.

The terminal apparatus was designed, manufactured and partly installed before the laying of the cables, in order that service might be given as soon as possible after they were laid. The design of the apparatus was based on the estimated characteristics of the cables but in order to provide for satisfactory operation, in case the attenuation and interference should exceed the expected values, the terminal apparatus was made adjustable over a wide range of amplifications and current levels.

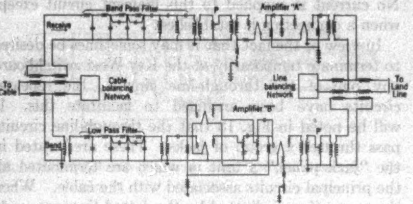
Band Pass Filter
P
Amplifier "A"
Receive
To Cable
Cable balancing Network
Line balancing Network
To Land Line
Amplifier "B"
Low Pass Filter
Send
P'

Fig. 12—Circuit of Telephone Repeater

Telephone Circuit

The telephone channels of the cables are connected to the land lines through bridge transformers and amplifiers as shown in Fig. 12. The third winding of each bridge transformer is connected through an amplifier to the center points of the line windings of the other bridge tranformer, thus forming the two-way, two-amplifier repeater circuit generally called a "22-type" circuit[12]. Since a close and constant balance has been secured between the cable and its network, as pointed out above, the repeater may be worked with large gains[13] even when the balance between the land line and its network is not close. Such is the case in terminating connections where the land end of the repeater is connected through the toll switchboard to subscribers' lines, as in calls to or from subscribers in Havana or Key West, without intervening toll lines of considerable length which could be balanced more closely.

Networks are provided to balance the average subscribers' lines as well as possible. When the repeater is to be connected to land lines of considerable length, networks of the general character described in an earlier paper[14], which provide a better balance for these lines, are used. Such networks are provided for use with the circuits extending north from Key West and also for use with the toll circuits in Cuba.

The repeaters combine the operating characteristics of "through-line" and "cord-circuit" repeaters. A through-line repeater is one which is permanently connected in a toll line, the whole forming a through-line circuit, no part of which is under the control of an operator at the repeater station. In a cord-circuit repeater the two line ends of the repeater circuit appear at the toll switchboard as plugs and this repeater cord circuit may be used to connect toll lines which terminate in jacks in the switchboard. Such a repeater is arranged so that the gain can be adjusted by the toll operator to the value specified for the circuits which it is used to connect. In the Key West and Havana repeaters the cable bridge transformers, the cable balancing networks and the amplifiers are permanently connected to the cables, the repeaters being thus through-line in character on the cable side. The repeaters at Key West on the through circuits are permanently connected to the land lines and their balancing networks, with certain arrangements for patching to be noted below. Such circuits are shown schematically in heavy lines in the upper part of Fig. 13. At Havana, and at Key West on the one circuit terminated there, the land sides of the repeaters terminate in the switchboard, so that these repeaters have some of the features of cord-circuit repeaters. These so-called "terminating connections" are shown in schematic form in Fig. 14. In the terminating as well as in the through-line circuits, the gains of the amplifiers are adjusted by means of the potentiometers *P* and *P'* shown in Fig. 12. These are set at the proper values by the repeater attendant. The control at the switchboard of the effective gains of the terminating repeaters is obtained by means of artificial lines or pads on the

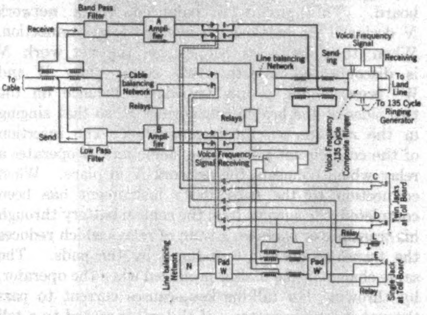
Band Pass Filter
Receive
A Amplifier
Voice Frequency Signal
Sending
Receiving
Line balancing Network
To Cable
Cable balancing Network
To Land Line
Relays
To 135 Cycle Ringing Generator
Relays
Send
B Amplifier
Low Pass Filter
Voice Frequency Signal Receiving
Voice Frequency -135 Cycle Composite Ringer
C
D
Twin Jacks at Toll Board
Relay
L
Line balancing Network
N
Pad W
Pad W'
E
Relay
Single Jack at Toll Board

Fig. 13—Circuit of Through Line Telephone Repeater

line and network sides of the bridge transformers *H* and *H'* as shown in the lower part of Fig. 14.

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[11] Van der Bijl, "The Thermionic Vacuum Tube and its Applications." McGraw-Hill Company, New York.

[12] Gherardi and Jewett, loc. cit.

[13] The term "gain" is extensively used in telephone and carrier practise to indicate amplification and is generally expressed in terms of the number of miles of standard cable, the attenuation of which it will just neutralize.

[14] Gherardi and Jewett, loc. cit.

In the terminating circuits, the land side of the repeater appears at the switchboard in both a single-jack and a twin-jack termination, as shown in Fig. 14. The single-jack termination is used for connections to local subscribers' loops and the twin-jack arrangement for connection to land toll lines. A call coming over the cable, indicated by the lighting of the signal lamp *L*, is answered with a single-plug toll cord, the plug being inserted in the jack *E*. If the call is intended for a local subscriber, the other end of the cord is plugged directly into the local circuit at the switchboard. This circuit is balanced by a network *N* designed to balance the average local connection. When the circuit is not in use the net work *N* is disconnected and the two equal pads *W* and *W'* preserve the proper impedance balance on the two sides of the bridge transformer *H*, so that singing in the repeater circuit is prevented. The insertion of the cord-circuit plug in the single jack *E* operates a relay which connects the network *N* in place. When connection to the subscriber's instrument has been completed, the current from the central battery through his transmitter operates a train of relays which reduces the transmission loss introduced by the pads. The same change in the pads is produced when the operator, by throwing her talking key, causes current to pass through her transmitter. If the call is routed to a toll line, the connection is made by the insertion of a "twin-plug toll cord" in jacks *C* and *D*, which disconnects the single jack circuit automatically. The twin plug at the other end of the cord is inserted in the jacks connected to the desired toll line and its balancing network. The circuit of this twin plug toll cord is shown schematically in the lower part of Fig. 14. In this case the operator may control the effective gain of the repeater by a key which changes the number of sections in the adjustable pads *V* and *V'*.

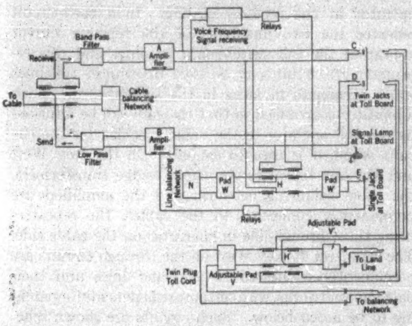

FIG. 14—CIRCUIT OF TERMINATING TELEPHONE REPEATER

In through-line use of the repeaters both amplifiers are continuously supplied with filament current and are maintained in operating condition. In cord-circuit or terminating use the amplifier which receives from the cable is kept in operating condition in order that signals may be received. When a connection is made through either the single- or double-jack circuits, relays are operated which cause current to be supplied to the filaments of the sending amplifier. No current is supplied to this filament circuit except when a connection is established.

In view of the fact that it may sometimes be desired to terminate temporarily at the Key West switchboard any one of the through-line circuits, the repeater circuits have been arranged to facilitate this. It will be noted in Fig. 13 that the through-line circuits pass through a group of jacks. These are located in the "jack panel," a unit in which are terminated all the principal circuits associated with the cable. When the connections indicated by the dotted lines are made the resulting circuit is the same as that of Fig. 14.

In order to protect the telephone apparatus against interference due to the telegraph channels, a filter system is connected in the telephone circuit between each amplifier and the cable bridge transformer. The filter in the receiving branch (Fig. 12) freely passes the range of frequencies (250 cycles to 2300 cycles) assigned to the telephone channel and greatly attenuates currents of all other frequencies. The filter in the sending branch prevents the passage of currents of frequencies which would interfere with the carrier telegraph channel.

FIG. 15—TELEPHONE REPEATER PANELS, JACK PANEL AND TESTING PANELS

The amplifiers, filters and other equipment of each repeater are mounted in a unit panel. These, together with the panels containing the terminal equipment associated with the other communication channels, are arranged in a double row in each terminal office. One of these rows is shown in Fig. 15. Four of the panels, two at each end, are repeater units, three of these being associated with the three cables. Owing to the importance of these circuits a spare unit has been provided to insure against interruption of service.

SIGNALING SYSTEMS

The signals for the telephone channels are transmitted over the cables by a "voice-frequency" signaling system, which involves the generation, transmission and reception of an alternating current, the frequency of which changes abruptly from 950 cycles to 1300 cycles and back, this alternation of frequencies taking place at the rate of 16 cycles per second. Signals are transmitted over the land lines north from Key West and over the toll lines terminating at Havana by means of the usual 135- and 16-cycle currents.

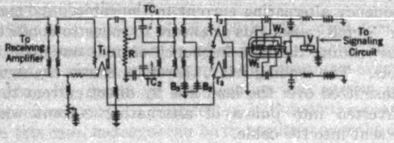

FIG. 16—RECEIVING CIRCUIT FOR VOICE FREQUENCY SIGNALING

By means of a ringing key in the toll cord circuit, the operator at one end of the cable causes the voice-frequency current described above to be sent out by the signaling oscillator, a vacuum-tube oscillator of the usual type arranged so that the capacity in the oscillating circuit is changed 32 times a second. This sends out alternately currents of the two different frequencies through the sending amplifier *B* (Fig. 14) to the cable. At the other end of the cable these currents flow into the receiving side of the repeater and through the amplifier *A*. If the telephone circuit is terminated at this point, part of the amplified signaling current passes into the receiving circuit for voice-frequency signals as can be seen from Fig. 14.

The details of the voice-frequency signal receiving circuit are shown in Fig. 16. The input impedance of this circuit is high so as to produce no appreciable loss in the telephone transmission circuit across which it is connected. The incoming signaling currents are amplified by the tube T_1, from which they pass into the high resistance *R*. Connected in series across this resistance are two tuned circuits TC_1 and TC_2, of which one is tuned to 950 cycles and the other to 1300 cycles. Each tuned circuit is connected through a transformer to the input side of a vacuum-tube rectifier. The grids of the tubes T_2 and T_3 are made just sufficiently negative by means of the batteries B_2 and B_3 so that there is normally no current flowing in the plate circuits of the tubes. The tubes thus function as detectors of incoming currents. When 950-cycle current is impressed on the circuit TC_1 a voltage is applied to the grid of tube T_2 causing current to flow through the relay winding W_1. The next instant rectified 1300-cycle current passes through winding W_2. The armature *A* of the polarized relay then vibrates back and forth at the rate of 32 times a second, thereby interrupting the current through the relay *V*. The armature of this relay therefore falls back, lighting the signal lamp *L* (Fig. 14) at the switchboard.

In the through-line circuits at Key West, such as the Havana-New York circuit, as shown in Fig. 13, the voice-frequency signaling current coming from the cable causes 135-cycle signaling current to be sent out automatically on the north-bound land line by a special type of "composite ringer" indicated in the upper right-hand part of this figure. The voice frequencies are received by a circuit similar to that just described and operate a relay which connects a generator of 135-cycle current to the land toll line, thus sending out this type of signaling current to call the distant operator. In through-line calls from the north 135-cycle current is sent over the land toll line to Key West. Here it enters the composite ringer and operates the voice-frequency sending set which puts on the cable the voice-frequency currents described above. These currents are received at the Havana toll office in the circuits shown in Figs. 14 and 16 and cause the operation of the signal lamp *L* at the toll board.

The receiving circuit for voice-frequency signals which is used in the case of terminating connections is included in the repeater unit. The composite ringers, which in the case of through-line circuits effect the change from voice-frequency signaling on the cables to 135-cycle signaling on the land lines, are mounted on the upper right-hand side of the relay rack shown in Fig. 17. Below the composite ringers are two oscillator sets for furnishing the 950- and 1300-cycle currents

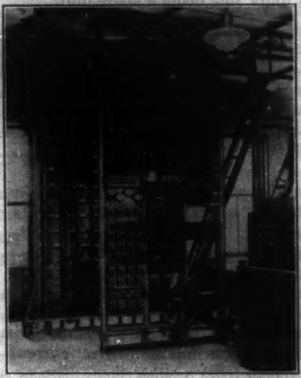

FIG. 17—RELAY RACK CONTAINING SIGNALING OSCILLATORS AND POWER CONTROL CIRCUITS

for telephone signaling over the cable, one of these being a spare unit.

CARRIER TELEGRAPH

A carrier telegraph terminal unit is permanently associated with each cable at both the Key West and Havana Offices. The circuits in the units used at the two terminals are the same, with the exception of the filters in the receiving branches. The carrier panels and their location with respect to the other apparatus are shown in Fig. 18. The four units containing vacuum tubes at the left of the row are the carrier telegraph units, one being a spare unit.

FIG. 18—CARRIER TELEGRAPH AND D-C. TELEGRAPH PANELS

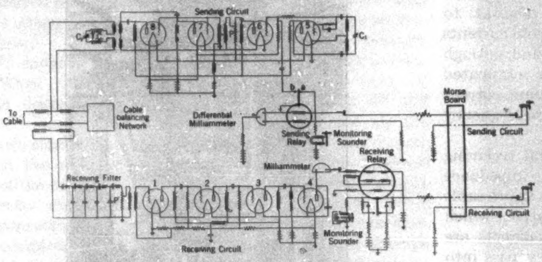

FIG. 19—CARRIER TELEGRAPH CIRCUIT

The operation of the carrier telegraph channel may be stated briefly as follows: Direct-current telegraph signals received from a subscriber's loop or other land line, actuate the sending relay in the carrier set, causing the oscillator to send through the cable high-frequency alternating current, interrupted in conformity with the signals. This alternating current enters the carrier receiving circuit at the other cable terminal, is rectified and actuates the receiving relay which sends direct-current telegraph signals into the associated land circuit.

The arrangement of the complete carrier terminal circuit is shown in Fig. 19. The details of carrier telegraph circuits have been described in an earlier paper[15] and only the outstanding features will be mentioned here. The armature of the sending relay[16] is normally held against the contact *a*. Under this condition the oscillator transmits a steady high-frequency current through the amplifier and tuned circuit to the cable. When a "spacing" signal is transmitted over the subscribers' sending loop, the armature of the sending relay moves to contact *b* which shunts the sending amplifier, interrupting the flow of high-frequency alternating current to the cable. A "marking" signal causes this armature to move to contact *a*, thus sending the high-frequency current out upon the cable. The sending relay, therefore, causes the signals transmitted over the land line by direct current to be converted into pulses of alternating current which are sent into the cable.

The outgoing high-frequency current passes through a two-stage amplifier, the last stage of which consists normally of one vacuum tube, either No. 7 or No. 8 in Fig. 19. By means of a switch at the carrier panel, the second tube may be connected in parallel with the first to increase the current. The output of the transmitter is controlled by the interstage potentiometer *P*. The current from the amplifier passes through a single tuned circuit *T C* in Fig. 19, which can be accurately tuned to the frequency of the outgoing current by means of the adjustable condenser C_2. The frequency of this current is controlled by the adjustable condenser C_1 in the oscillator circuit.

At the other terminal of the cable the high-frequency alternating current passes through the bridge transformer and receiving filter. Since the attenuation of the cable for the carrier currents is high, the received current is passed through a multi-stage amplifier before it reaches the detector which rectifies it and causes it to operate a sensitive receiving relay. As shown in Fig. 19, the receiving relay retransmits the signals by means of direct current over the subscriber's receiving loop. The receiving circuit differs from that used in land carrier telegraph systems in the following features: Instead of the usual double tuned circuit for selecting the proper frequency, a narrow-band, highly selective fixed filter is placed before the amplifier. The gain attainable in the receiving amplifier is much higher than is provided in land-line systems. When less than the full gain is required tube No. 1 can be cut out by means of a key.

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[15] Colpitts and Blackwell, loc. cit.

[16] For clearness and simplicity in showing the relation of the relays to the telegraph circuits the conventional representation of relays shown in Fig. 19 has been used in this paper. It is to be understood that the windings shown within the circle, act to magnetize the armature which moves back and forth between the poles of a permanent magnet, its position at any time depending upon the polarity of the resultant magnetism in it.

The sending and receiving carrier telegraph circuits work directly into subscribers' loops at Havana. In through-line traffic, which is the only type of telegraph traffic now required at Key West, the carrier circuits are arranged to operate standard land-line duplex telegraph sets. The d-c. telegraph circuits from the carrier apparatus pass through jacks in the morse boards for convenience in connecting them to any desired land lines or subscribers' loops.

The arrangement of Fig. 19 is that used for full-duplex operation, that is, when it is desired to transmit messages simultaneously in both directions over the cable. By means of a switch on the carrier panel the circuit may be adapted to half-duplex operation. In this case, messages can be transmitted over the cable in both directions but not simultaneously.

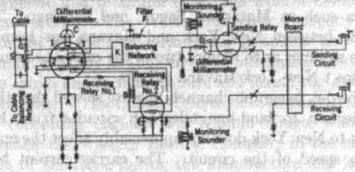

Fig. 20—Direct-Current Telegraph Circuit

Direct-Current Telegraph

A direct-current telegraph unit is permanently connected at each end of each cable as a repeater of telegraph signals between the submarine cable and a land circuit. The four units at the right of Fig. 18 are the direct-current telegraph panels, one being a spare unit. A schematic diagram of the direct-current telegraph circuit arranged for repeating between the submarine cable and subscriber's loops, is shown in Fig. 20. This figure shows the arrangment for full-duplex operation over the cable.

In this telegraph circuit the separation of the sending and receiving branches is accomplished by the main-line receiving relay, which in its relation to these branches functions like a bridge transformer. Outgoing signals to the cable divide at the points *T*, half the current passing through coils 1 and 2, and the other half passing through coils 3 and 4. These coils are wound so that with a good balance between the balancing network and the circuits on the opposite side of the relay, the armature *A* is not actuated by the sending currents. It is evident, however, from Fig. 20 that incoming signals from the cable will produce an additive effect in passing through the relay coils and operate this relay.

The network *K* balances, for the frequencies involved in direct-current telegraph operation, the impedance between the points *S* and *S'*. Reference to Figs. 10 and 20 shows that this includes the two halves of the filter *G* in parallel, the cable and the cable balancing network as well as the impedance at these frequencies of the telephone and carrier apparatus. The network contains a fixed portion to balance the filter *G* and an adjustable portion to balance the cable and the associated equipment just mentioned. The balance can be tested by observing the differential milliammeter *C* (Fig. 20) as signals are transmitted from the sending branch.

Signals coming from the subscriber's sending loop operate the sending relay which acts as a pole-changer to reverse the polarity of the 10-volt battery applied to the cable, in conformity with these signals. The low-pass filters *F* and *G* transmit freely all frequencies below about 80 cycles but practically prevent the passage of higher frequencies. They thus allow free passage of those components of the sending currents which are necessary for the operation of this system, but suppress those which might cause interference in the telephone and carrier channels.

A feature of the receiving branch is the tandem connection of receiving relays. Incoming signals from the cable actuate the sensitive receiving relay No. 1 and, as shown, in Fig. 20, the operation of this relay in turn actuates the receiving relay No. 2. The armature of receiving relay No. 2 acts as a pole-changer to transmit signals to the receiving loop. The larger energy available for the operation of this relay enables it to commutate successfully the comparatively heavy currents which are transmitted into the land line. The networks connected between the armature and the contacts of receiving relay No. 2 operate to suppress sparks at break. The purpose of the transformer *B* is to quicken the action of the receiving relays.

The circuit as shown in Fig. 20 and described above is adapted to working into two loops for a local telegraph subscriber. Apparatus equivalent to a standard duplex set is provided in the telegraph panel so that by throwing a switch, the set may be adapted to duplex operation over a land line. This is the condition at Key West where all the telegraph circuits are continued northward. Switches are also provided in the panel for adapting the circuit to half duplex operation instead of full-duplex operation.

The sending loops, the receiving loops and the 120-volt batteries of the land sides of the direct-current telegraph units are connected through jacks in the standard Morse Boards so that they may be available for cross-connecting or testing.

Auxiliary Equipment

A jack panel and two testing panels in each terminal office provide means for testing the circuits and terminal apparatus and for changing their connections. The jack panel contains a system of jacks to which all circuits are connected and on which are terminated all important pieces of equipment such as amplifiers, filters, networks and bridge transformers. The testing panels contain an oscillator for supplying testing currents of telephone and carrier frequencies, transmission measuring apparatus for testing the telephone repeaters and circuits, apparatus for testing the balance of the networks and lines, thermocouples and meters for measuring the carrier currents, a frequency meter for testing their frequencies and apparatus for testing the efficiency of the carrier terminal sets. In Fig. 15 the jack unit is at the middle of the row of panels, with a testing unit on each side.

A 24-volt storage battery furnishes current for the filament circuits of all the vacuum tubes in the telephone repeaters, carrier telegraph panels, ringer circuits and testing apparatus. Positive and negative 120-volt batteries are provided for the standard duplex sets and for the local circuits of the carrier and direct-current telegraph sets. The positive 120-volt battery also furnishes plate current for all vacuum tubes. Grid potentials for the vacuum tubes are derived from a small capacity 60-volt storage battery. A number of 10-volt batteries are provided for the direct-current telegraph circuits over the cables. All batteries are charged from the local power mains through mercury arc rectifiers, with gas-engine-driven generators for charging in case the electric power supply fails. Battery circuits for supplying the terminal equipment pass through control apparatus mounted on the relay rack shown in Fig. 17. On the two sections at the left are rheostats for adjusting the filament currents of the vacuum tubes, with associated relays and resistances in these circuits, and also meters for measuring the filament and space currents and the voltages used. Another rack, not shown, carries the fuses and other protective equipment associated with the power supply.

OPERATION

The relation between the total transmission equivalent of the telephone channel over the cables, the available gains in the terminal amplifiers and the balance obtained between the cables and the balancing equipment was such that this channel could be operated at an efficiency materially higher than that required for connections terminating in Havana and Key West and also over a large range of current levels. As the cables were to be used in general as links in long circuits, the operating adjustments which were finally adopted were set rather by the circuits as a whole than by the cables. One of the cables was connected at Key West to a land line to form a direct New York-Havana circuit, a second cable to form a direct Jacksonville-Havana circuit and the third was arranged for a Key West-Havana circuit.

The New York-Havana circuit was set to have a transmission equivalent of 12 miles of standard cable. As the New York-Key West section has an equivalent of 10 miles, the net equivalent of the cable and terminal apparatus is only two miles. The Jacksonville-Havana circuit was set at 11 miles and the Key West-Havana at 10 miles. Switching through New York, operating equivalents are obtained for Havana-Chicago connections of approximately 16 miles and for Havana-San Francisco[17] of 20 miles. In addition to the submarine cables, the Havana-Chicago circuit contains 2453 miles (3940 km.) of land line and the Havana-San Francisco 4790 miles (7700 km.)

With these equivalents, satisfactory commercial connections can be established not only from Havana to points on the eastern part of the United States, but also to the Pacific coast. The application of repeaters to the Cuban toll lines makes it possible to establish commercial connections from points along the island to points in the United States. While the majority of the telephone connections over the cables have been for calls between New York and Havana, commercial calls have been handled satisfactorily to points all over the United States, such as Boston, Washington, Chicago, St. Louis, San Francisco, New Orleans and Atlanta, also to Toronto and Montreal in Canada, and to points in Cuba such as Matanzas, Sagua, and Santiago. The traffic between New York and Havana has been so large at times as to require two of the cables to be used in direct New York-Havana circuits.

The d-c. telegraph channels operate so well that their connection to land-line telegraph circuits from Key West to New York does not appreciably affect the maximum speed of the circuit. The carrier-current telegraph channels are good enough for the operation of four channel multiplex printers if it should be desired to use them for such service.

In planning this cable system it was intended that a demand for more telegraph facilities would be met by increasing the number of carrier channels per cable. As has been noted, the initial apparatus and land connections provided for the commercial operation of only six telegraph channels, one d-c. and one carrier channel per cable, on the basis that this number would meet the initial service requirements. In order, however, to obtain information regarding the operation of additional carrier channels and to provide spare telegraph facilities in case of cable failures, a fifth carrier telegraph set was provided at each terminal, together with special receiving selective circuits. With this apparatus three carrier telegraph channels were successfully operated over one cable, using frequencies up to 4200 cycles, for which the equivalent of the circuit between the terminal offices is 48 miles. It is possible that this number of channels can be further increased. The present arrangement of the carrier telegraph apparatus makes it possible, therefore, to carry six telegraph channels over two cables or four over one cable. This will prove very useful in maintaining service in case of cable failures.

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[17] The transcontinental line has been improved since the publication of the paper "Telephone Repeaters," Gehrardi and Jewett, TRANS., A. I. E. E., 1919. The transmission equivalent of the New York-San Francisco circuit is now approximately twelve miles.

At the time of the opening of service over these cables under the auspices of the Pan American Union, greetings were exchanged between the President and other officials of the United States at Washington and the President and officials of the Cuban government at Havana. In connection with this demonstration, the circuit was extended through New York and San Francisco to the Island of Santa Catalina, off the coast of California, in the Pacific Ocean. As this island is connected to the mainland by radio telephone[18], this connection, 5470 miles (8800 km.) in length, involves the radio connection through the air, a 5322-mile land line across the United States and the submarine cable from Key West to Havana. This circuit containing twenty-five telephone repeaters illustrates the possibilities of the present state of development of telephony.

The work described in this paper involved the application of ideas from practically all branches of the telephone and telegraph fields and from a number of organizations. The Western Electric Company was retained by the Cuban-American Telephone and Telegraph Company as engineers and purchasing agents for the cables and to manufacture and install the terminal apparatus. The Cuban Telephone Company retained as consulting engineer Sir William Slingo, who also assisted the Western Electric Company in the inspection of the cable during the manufacture and laying. The electrical design of the cables, the method of operation, the design and arrangement of the terminal apparatus and the adjustment of the system for operation were the work of the engineers of the American Telephone and Telegraph Company and the Western Electric Company. The Telegraph Construction and Maintenance Company, Limited, of London, which manufactured and laid the cables, was largely responsible for the mechanical features of the cables, such as the design of the armoring for the different depths of water involved and the arrangement of the copper tapes. The recommendations of the engineering firm Clark, Forde and Taylor, retained by the Western Electric Company, were obtained on many of these matters including the routes to be followed.

Discussion

Bancroft Gherardi: The two questions that required much care and thought in the design of this cable were, first—shall the cable be continuously-loaded or coil-loaded, and, second, shall it be a single or a multi-conductor construction? There were serious questions involved in each. In the first place, as to the loading. Coil-loading is in many respects more efficient than continuous-loading, because with coil loading, you can get practically any inductance per mile that you desire, and so you can, within very considerable limits, increase the efficiency of the circuit. With continuous-loading, however, there are very sharp limitations on the possible inductance per mile that can be attained with any practical contruction. As we saw the problem at that time, and as we still see it, the coil-loading would have been chosen, for electrical reasons, but it presented most formidable mechanical difficulties. In the first place, the making of a cable of that kind, interrupted periodically by coil cases and coils, and laying it in deep water was a very formidable matter. In the next place, the maintenance of the cable would necessarily be complicated by having points of discontinuity. The attachment of the cables to the coil cases and the coil cases themselves would necessarily be elements of weakness. This weakness is not serious in a land cable, as trouble, if it occurs in a land cable, can be cleared in a few hours. On the other hand, if trouble develops in a cable of the kind in question, it may be weeks and under bad weather conditions and unfavorable location of cable ships, it might be months before the trouble could be cleared. The coils were, therefore, excluded for mechanical reasons.

The other question was the one of the single-conductor versus the multi-conductor cable, and this brought up a related question that of one cable versus several cables.

These questions, as you see, are tied right up with each other. The single-conductor cable necessarily meant grounded-circuit operation. In the case of the metallic circuit cable, the obvious method of operation would be to build probably a cable of four wires and undertake to operate two physical metallic circuits, and possibly a phantom circuit, with a more remote possibility of getting a fourth circuit, that is, a grounded phantom circuit from the combination.

The choice finally was determined by the consideration that we could not afford to put all of our eggs in one basket, as we might lose the whole cable at one time. Therefore the alternative of three separate cables was chosen, although it required a great deal of study and investigation as to the general question of the grounded circuit operation of cables of that character, and their operation under the particular conditions existing between Key West and Havana. Our investigation satisfied us that we could safely count on that method of operation.

These investigations were very extensive and very carefully made. We satisfied ourselves that the cable itself, and the service from it with any degree of amplification we would wish to place on it, would be satisfactory.

William McClellan: What effect is long distance wireless communication going to have on long distance telephone? At present there is a certain lack of secrecy which our customary long distance lines give in part at least.

Bancroft Gherardi: I will be glad to say a word in answer to the question which has been asked. The matter of utilizing wireless in that connection was very carefully considered at the time the cables were being considered and it has been reconsidered recently in this form—if we were to do the job again, would we do it by means of wire or wireless? In each case the answer has been the same. Most of the communication has been on business, matters—particularly last spring, and to a certain extent this fall, there were a number of very serious financial failures avoided by the use of the cables. These were matters which required prompt communication with a considerable number of different institutions, and if action was not taken in twenty-four hours there would be a financial failure, and there was a situation in Cuba in which a few failures might start things going and create a very much more serious state of affairs than the one which actually existed.

Obviously, wireless communication, certainly in the present state of the art, would have been entirely unsuited for such service.

The mere mention of such topics in the air, the broadcasting of such questions as were discussed in these communications would create the effect which it was desired to avoid. But excluding altogether the matter of secrecy, and excluding altogether the matter of interference, atmospheric or otherwise, we have thus far been unable to figure out how we could give an equally extensive and dependable service and give it as cheaply by means of radio across that distance, as we can by means of the cables.

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[18] Clement, Ryan and Martin, "The Avalon-Los Angeles Radio Toll Circuit." *Proc. I. R. E.*, Dec. 1921.

Submarine Cable Telegraphy

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The history of the development of the subject is first outlined, and methods of operation of cables are described. The technical side is introduced with a statement of the various conditions which limit operation of cables, and a general method of analysis is developed, based upon an extension of ordinary alternating-current theory. The theory is made use of to analyze the action of cable types and of apparatus which at this time can be regarded as standard. The fundamental theory of the method of analysis, with information on the calculation of transients in electrical circuits, is given in the Appendix.

HISTORICAL

THE feasibility of submarine cable telegraphy was suggested by Salva, a Spaniard, as early as 1795. The first actual experiment seems to have been made in 1803. In the period covered by the next forty years, numerous experiments were carried on in different parts of the world for the purpose of demonstrating the possibility of submarine telegraphy. In 1842, Morse transmitted signals over a short section of insulated wire laid in the New York Harbor. The conductor used in this experiment was insulated by covering it with hemp soaked in tar and pitch, and surrounding this with india-rubber. The introduction of gutta-percha as an insulator and the invention of a machine for applying it to wire, gave a decided impetus to the experiments being carried on.

The first commercial attempt to establish electrical communication by submarine cable was in 1850, when a cable was laid between England and France. This cable was broken, however, shortly after communication was established. The cable used in this attempt consisted of a No. 14 copper wire surrounded by gutta-percha to a thickness of one-half inch. The failure of this cable due to its physical weakness led to the design and laying of an improved type between Dover and Calais in 1851. This cable consisted of four No. 16 copper wires, each covered with two layers of gutta-percha to the size of No. 1 gage. These insulated wires were armored with ten No. 1 galvanized iron wires wound spirally. This cable proved to be successful, and in the next few years a number of cables was laid between England and adjacent shores, between Denmark and Sweden, and in the Mediterranean Sea.

The first attempt to lay a cable across the Atlantic was in 1857. This attempt ended in failure when the cable broke in 2000 fathoms of water, at a point about 350 miles west of Valentia, Ireland. As at that time there were no means of recovering a cable in deep water this project was abandoned. In August 1858 the same company, The Atlantic Telegraph Company, completed the laying of a cable. This cable was operated for about three months, when it became interrupted, and no attempt was made to repair it. In the years 1865 and 1866 The Atlantic Telegraph Company laid two new cables. The first cable broke when it was about two-thirds laid. The second cable was then successfully laid, and soon afterward the end of the first cable was picked up with much difficulty and its laying was completed. These cables were operated with no competition until 1869 when the French Atlantic Telegraph Company opened a cable for traffic. With the success of the Atlantic cables established, the growth of submarine cable systems was rapid, until in 1914 there were seventeen cables across the Atlantic between North America and Europe alone, and there was then an aggregate of about 2000 cables in the world, comprising a total length of over 300,000 miles.

The use of gutta-percha as an insulator was adopted at the very inception of submarine cables, and it is still almost universally used for long cables.

The necessity for a protective armor for submarine cables was demonstrated by the failure of the first cable laid in the English Channel. Since that time cables have been provided with a protective armor consisting of a number of iron or steel wires wound spirally around the core. The design of the armor was, of course, changed from time to time as experience demonstrated the desirability of improvement.

Even before the first Atlantic cable was laid it was realized that a very sensitive instrument would be necessary for the successful reception of signals on long cables. Early in 1858 Prof. William Thomson, later Lord Kelvin, perfected an invention that was destined to fill this need. This instrument known as the mirror galvanometer, consisted of a small permanent magnet, with a small mirror fixed to it, suspended by silk fibers and surrounded by a coil of fine wire. By reflecting a light from the small mirror to a screen, a greatly magnified image of the coil movement was obtained. When the 1858 cable was completed, tests showed that signals transmitted with a battery of Daniell cells could be successfully received with the mirror galvanometer. However, when the cable was turned over to the electrician for working, he, believing that a high voltage was best suited for signaling, used a large induction coil, excited by a battery, which yielded a potential estimated at about 2000 volts. Under the strain of this voltage, the insulation began to break down and the signals gradually failed. The mirror galvanometer and Daniell cell battery were then substituted and the cable was successfully worked for a

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short time until the cable finally failed completely. It was the opinion at that time that the high voltage used at first had partly broken down the insulation of the cable, and that the faults thus opened gradually became worse until the insulation failed completely.

The mirror galvanometer, with improvements from time to time, was used universally on long cables for a number of years. In 1867 the siphon recorder was invented. This instrument, which had the advantage of supplying a permanent record of the signals as received, gradually replaced the mirror galvanometer, and in its improved forms it is now largely used in the operation of long cables. Previous to 1871 cables were operated in one direction only, but in that year the duplex system was introduced, which permits the use of the cable for simultaneous transmission in both directions. Other more recent developments of operating apparatus include cable relays, automatic transmission, and cable magnifiers, the latter being introduced about 1908. These developments will be described later.

The maximum operating speed of the 1858 cable before it failed was about 15 letters per minute. When the cable was first opened it required about thirty hours to transmit a message of 150 words from President Buchanan to Queen Victoria. It is interesting to note that at that time the minimum rate on a message from New York to London was £20 for a twenty-word message and £1 for each additional word. From that time until the present, improvements in the cable systems have been such that it is now possible to duplex a good Atlantic cable with an operating speed of 300 letters per minute each way; and the operating economies effected have been such that the maximum cable rate between New York and London is now twenty-five cents per word.

CONSTRUCTION AND LAYING OF CABLES

The make-up of a typical deep-sea submarine cable is shown in Fig. 1. The conductor is made up of stranded copper wires, or of copper strips. The actual size of the conductor and of the insulation is determined by the operating characteristics desired.

As previously stated, the insulation generally used in submarine cables is gutta-percha. Gutta-percha is derived from the milky sap of gutta trees. The sap of several different species of trees is suitable for converting into gutta-percha, the quality of the gum from some species being better than that from other species. These trees are found principally in the Malay Islands and Peninsula and in Borneo. The sap is collected from incisions in the bark of the living tree, or by stripping the bark. The gutta is roughly cleansed after its collection, and is coagulated into solid cakes in which form it is imported. In the manufacture of the finished product, the gutta must be further purified and treated before it is suitable for use as insulation.

Another form of insulation, known as "balata" or "gutta-balata," is derived from the sap of a species of trees found in some parts of South America. This has been used in combination with gutta-percha in short telephone cables, and possesses distinct advantages for that purpose. The possibility of using balata for long submarine telegraph cables has been suggested.

Rubber has also been used for insulation of submarine cables, notably for the cable connecting the United States and Alaska. This material is somewhat inferior to gutta-percha for the purpose.

It is necessary to protect the gutta-percha from damage by the iron sheathing by placing some sort of a cushion between them. In modern cables this cushion is generally made up of several layers of jute. Jute consists of the bark fibers of two plants called the "chouch" and "isbund," extensively cultivated in Bengal. The jute is usually tarred or tanned before being used on a cable.

In order to protect the core of the cable from damage after being laid, it is necessary to provide a layer of sheathing or armor wires. These wires also serve to support the cable while being laid, and in case it is later necessary to lift the cable for repairs. The design depends upon the type of cable—whether deep-sea, intermediate, or shore-end—and in general consists of a number of galvanized iron or steel wires wound spirally. The shore-end types of cables may have two layers of sheathing wires. As a preservative, the sheathing is covered with a layer of jute.

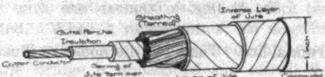

Fig. 1—Typical Section of Cable

The route for the cable is so far as practicable chosen to avoid deep water, sudden changes in depth, and rocky bottoms. The greatest depth of transatlantic cables is 2.9 statute miles; across the Pacific the cable depth reaches 3.4 miles.

The manufacture of submarine cables has been largely a British industry due to their early interest in and need of a communication system between the various parts of the Empire. The Alaskan Cable is the only long submarine cable that has been manufactured in the United States.

MODERN OPERATION AND APPARATUS

The following description of apparatus used in regular operation of cables does not aim at being complete. Many devices are developed from time to time for application to cables; some of these are of permanent value and others are of only passing interest. It is the purpose to describe here only some of the important appliances which may be regarded as standard.

Duplex Operation. Generally speaking, a greater output can be obtained by duplex operation of a cable than by operating in one direction only. Accordingly, cables are ordinarily worked duplex except in cases where it is impossible to maintain a satisfactory duplex balance.

In order to duplex a cable, it is necessary to provide some arrangement by which the receiving instrument is not responsive to outgoing signals, while at the same time it must respond to signals coming from the distant end. There are two common methods of duplexing a communication circuit, both of which involve the use of an artificial line. These two methods are illustrated in Fig. 2.

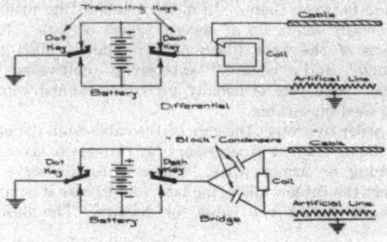

FIG. 2—DUPLEX TERMINAL SETS

In the differential system of duplexing, the coil of the receiving instrument has two separate windings. These are so joined to the cable circuit that in transmitting, the currents in the two windings are equal in magnitude and opposite in direction, thus causing no effect in the local receiving instrument; while currents from the distant station pass through the two coils in the same direction, and cause the receiving instrument to respond.

The bridge method of duplexing employs the principle of the Wheatstone bridge, and is almost universally used for cable working. There is some latitude in the arrangement of the bridge; thus the two condensers may be replaced by resistances or by inductances—the latter arrangement being used by some cable companies. Another plan is to use condensers shunted by high resistances. The use of condensers appears to have advantages for high-speed working of cables, in that it results in better shaped signals.

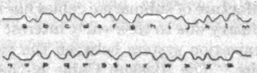

FIG. 3—LETTERS OF THE ALPHABET RECEIVED ON SIPHON RECORDER

The Standard Cable Code. The continental Morse code is mostly used for operation of submarine cables. The method of distinguishing dots and dashes is ordinarily different, however, from that in land-line or wireless telegraphy. In land-line or wireless operation the difference between dots and dashes is one of duration, the dash being about three times as long as the dot. In submarine telegraphy the dots and dashes are of the same duration but of different polarity. Dots are formed by applying positive potential to the cable; dashes by applying negative potential. The spacing intervals are obtained by earthing the cable, the zero interval between letters being one unit, and between words usually three units. Fig. 3 shows the alphabet as received on a siphon recorder tape.

Transmitting Apparatus: The Cable Key. For signaling on the cable it is necessary to apply positive, negative or zero potential to the sending end of the cable in various combinations as explained above. In manual signaling a special double-lever key known as the cable key is used. This is shown in theory in Fig. 2. In the normal position of the cable key, both levers are up, thus grounding the cable. When the dot lever is depressed, positive potential is applied to the cable, and when the dash lever is depressed negative potential is applied to the cable.

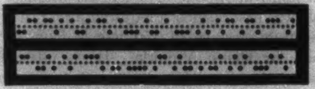

FIG. 4—TRANSMITTING TAPE WITH LETTERS OF THE ALPHABET

Manual transmission is employed chiefly in conversations between stations relative to the operation of the circuit.

The Automatic Transmitter. In handling commercial messages a motor-driven automatic transmitter is commonly used in place of manual transmission.

A paper tape is first prepared with perforations corresponding to the message to be transmitted. A sample of this tape with perforations corresponding to the letters of the alphabet is shown in Fig. 4. The tape is passed through the automatic transmitter at the desired speed. The keys shown in Fig. 2 are controlled magnetically from contacts in the transmitter, these contacts in turn being operated in correspondence with the perforations in the tape.

A device known as a perforator is used in preparing the paper tape. The modern perforator has a keyboard similar to an ordinary typewriter and is operated similarly. An electrical solenoid furnishes the power for punching the holes, and the tape is automatically stepped forward.

Receiving Apparatus: The Siphon Recorder. This instrument is generally used in the recording of received cable signals. It is in principle a D'Arsonval galvanometer, with a moving coil suspended between the poles of a strong magnet (Fig. 5). The coil is in the form of a rectangle, a common size being 6 cm. long and 1.8 cm. wide. The coil may be wound to have 500 to

800 ohms resistance. The coil controls the movement of a fine glass siphon pen supplied with ink. The movements of the pen are recorded on a paper tape drawn at uniform speed beneath the siphon. The coil and siphon are separately mounted, and are connected by silk fibers arranged to magnify the motion of the coil. To reduce friction between the siphon and the tape, the siphon is vibrated vertically with respect to the tape. This is accomplished by an electric buzzer arrangement, the armature of which is connected to the siphon by a silk fiber.

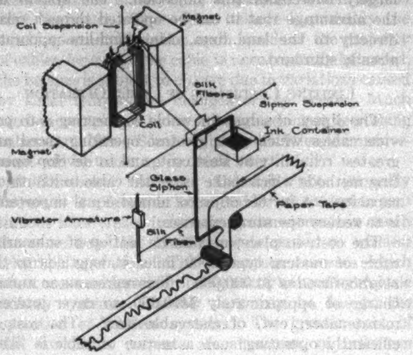

Fig. 5—Moving Elements of Siphon Recorder

The coil and the siphon are suspended by fine wires the tension of which may be varied, thus permitting the natural period of the moving system to be adjusted according to the speed of the incoming signals. For the recording of well-shaped, undistorted signals, it is necessary that the coil return to its zero position quickly when the current flow ceases, and it is also necessary that the coil shall not swing beyond its zero position. It is sometimes necessary to provide damping for the moving system, which may be accomplished electromagnetically by having the coil shunted with a high resistance, or may be secured by having a small aluminum vane attached to the coil and moving in oil.

A siphon recorder gives a readable signal when actuated by from 30 to 100 microamperes, (0.000030 to 0.000100 ampere).

Magnifiers. In order to increase the speed of a cable above a point where satisfactory operation can be obtained with a siphon recorder alone, it is necessary to magnify the weakened signals before passing them through the recorder. With the magnifiers described below, good signals may be obtained when the current in the magnifier coil is as small as from two to fifteen microamperes.

The Heurtley Magnifier. One type of magnifier extensively used was patented by E. S. Heurtley. This magnifier (Fig. 6) is similar in principle to a siphon recorder, with the coil controlling the movement of two fine platinum wires. Associated with the two moving wires are two similar fixed platinum wires, the relative positions of which are indicated in the figure. The platinum wires are heated by battery current. When the relative positions of the wires are changed by movement of the coil from its mid-position, the mutual heating effect between the fixed and moving wires is altered. Thus the temperature and hence the resistance of the wires in one arm of the bridge are increased, the values being decreased in another arm. The resulting bridge unbalance causes a current to flow in the siphon recorder.

The Selenium Magnifier. The selenium magnifier, also used in operation of long cables, was developed by T. B. Dixon, K. C. Cox and others. It is also of the moving-coil type, the coil carrying a small mirror. This mirror reflects a strong beam of light on to a bank of two or four selenium cells, which form either two or four arms of a Wheatstone bridge. Battery is connected across one diagonal of the bridge and the ordinary siphon recorder is placed in the other diagonal. The electrical resistance of selenium cells varies inversely with the strength of light to which they are subjected. When a movement of the magnifier coil causes a movement of the light beam on the selenium cells, the bridge is unbalanced and current flows in the siphon recorder.

The Vacuum-Tube Magnifier. Some experimental work has been done on the application of vacuum-tube magnifiers to cable operation and fair results have been obtained. There has not been a large incentive to developing the vacuum-tube magnifier, because of the condition that other fairly satisfactory magnifiers were already available.

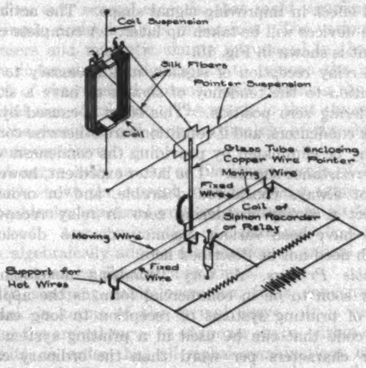

Fig. 6—Heurtley Magnifier

Cable Relays. In some cases it is desirable to repeat signals automatically from one section of cable into another rather than to record them. It is essential that a cable relay used for this purpose shall have a reliable form of electrical contact. All of the standard types of cable relays employ the principle of the D'Arsonval moving-coil galvanometer, and differ only in the method of making contact. A relay may be used with or without a magnifier in circuit, the relay alone being approximately as sensitive as a siphon recorder.

The Brown drum relay has an iridium-pointed platinum wire, the movement of which is controlled by the relay coil, making contact on the insulated silver rings of a rotating drum. With very little pressure the iridium point makes good contact on the moving silver, and the friction resisting the lateral movement of the contact point is small.

In the Muirhead gold wire relay, the coil controls the movement of a gold wire between two platinum contacts. The gold wire is maintained in rapid vibration by an electric buzzer arrangement, for the purpose of securing better contact.

The Bruce relay contact scheme consists of a fine nickel wire controlled by the moving coil, which makes contact in drops of mercury. The nickel wire is rapidly vibrated vertically with respect to the contact surfaces, thus reducing frictional resistance to its lateral motion.

Shaping of Signals. In addition to apparatus previously mentioned, various auxiliary devices are used in order to shape properly the received signals. Such devices comprise coils known as "magnetic shunts" connected in parallel with receiving equipment, condensers in series with receiving equipment, and various special pieces of apparatus. The use of condensers in the bridge arms (Fig. 2) has a very beneficial effect in improving signal shape. The action of these devices will be taken up later. A complete cable circuit is shown in Fig. 10.

In relay reception of signals, it is necessary to pay attention to the tendency of signals to have a slowly wandering zero position. This effect is caused by the block condensers, and if conditions are otherwise correct it may be eliminated by providing the condensers with high-resistance shunts. The latter expedient, however, is not always considered desirable, and in order to correct a slowly wandering zero in relay reception, there have been various ingenious devices developed which need not be described here.

Cable Printers. A very promising development, likely soon to be in commercial form, is the application of printing systems of reception to long cables. The code that can be used in a printing system has fewer characters per word than the ordinary cable code. In addition to the economies made possible by the use of a shorter code, a cable printer is also likely to effect economies in operation due to the fact that fewer attendants will be required than with the present system.

Eastern Telegraph Company's System. The Eastern Telegraph Company has recently patented a system of operation which is quite different from conventional methods of operation. In this system the original—not the modified—continental code is used. The original continental code would ordinarily be less efficient, but some special apparatus has been developed which largely overcomes this objection. The system has the advantage that it can be operated through relays directly to the land lines, using land-line apparatus already standard.

LIMITING CONDITIONS OF CABLE OPERATION

The object of submarine cable engineering is to provide cables which give greatest operating speed and greatest reliability at least cost, and to develop operating methods which make use of the cable to its utmost capacity. A further object of almost equal importance is to reduce operating expenses.

The cost, in place, of a single section of submarine cable of modern type 2000 miles in length is in the neighborhood of $4,000,000. This represents an annual charge of approximately $400,000, to cover interest, maintenance, etc., of the cable itself. The cost of efficiently operating such a section of cable is likely to be in the neighborhood of $200,000 per year, for salaries of men and apparatus directly used in handling traffic. From these figures it is evident that considerable engineering can be justified to obtain highest working efficiency of cables.

A cable of modern type 2000 miles long would have approximately 3000 ohms resistance and 800 microfarads electrostatic capacity to ground. The operating speed, or the message capacity, of a cable is directly limited by its resistance and capacity. The resistance and capacity can be reduced in designing a cable only by increasing the size of the cable, which proportionately increases its cost.

Besides the constants of the cable itself, there are other factors which act in different cases to control the ultimate speed of a cable. These factors are enumerated below.

1. *Sensitiveness of Receiving Apparatus.* If a cable is worked at a very low speed, it is possible to transmit sufficient energy through it to operate receiving apparatus which is substantial in construction. When the speed is increased the current transmitted through the cable falls off very rapidly, due to the effect of resistance and capacity. The decrease in received current is met as far as practicable by providing receiving apparatus of increased sensitiveness. If the apparatus is not sufficiently sensitive, the operating speed may be definitely limited thereby—in fact it may be said that previous to ten or fifteen years ago, cable speeds were definitely limited by the lack of sensitiveness of available receiving equipment. Since that time, however, cable magnifiers, to which reference was previously made, have been developed to a point where they are practically as sensitive as is desired. While there is still some room for improvement the sensitiveness of

available magnifiers is such that other factors, given below, now largely limit the speed.

2. *Duplex Balance.* Due to small but unavoidable errors in the artificial line necessary for duplex working, there is likely to be some degree of off-balance, causing extra currents in receiving apparatus which act to limit the speed. The duplex balance is probably the most important limitation upon speeds of the majority of cables, for even if the cable is once correctly balanced, the balance is subject to change due to variations caused by small temperature changes of the ocean. Much can be accomplished by careful engineering in decreasing balance troubles. Some of the possibilities of improvement will be taken up in detail later.

3. *Extraneous Current.* Although not generally known, it is a fact that ocean cables are subject to continuous interference from extraneous currents in much the same way that interference is caused to wireless telegraph operation. The extraneous currents which affect ocean cables are probably partly caused by electric railway systems. Possibly part may be due to the operation of wireless systems. The greater part of the extraneous currents are, however, of unknown origin, and are doubtless akin to the "static" so familiar to wireless operators. The current is very irregular in nature and may be considered to contain currents of all frequencies. In practise it is usually found that extraneous currents are smaller in magnitude than the currents present due to slight errors in the duplex balance, although in some cases the extraneous currents are the larger. If the balance is improved extraneous currents become of increased importance, and they must be regarded as forming an ultimate limit to further increase in speed of a cable.

It is customary to make use of an earth connection for cable working which is extended several miles from shore. By this means disturbances from electric railway systems are largely reduced. Currents from other sources may be somewhat decreased by the same expedient, although they can not be eliminated. Extraneous currents may be picked up at any point along the cable and conveyed into the receiving apparatus, although the greater part is introduced by slight unsteadiness of the sea-earth connection, of amounts ranging from 0.0001 to 0.005 volt or higher.

4. *Sending Voltage.* The amount of voltage used for operating the cable has a bearing upon the operating speed. A short section of gutta-percha cable is capable of withstanding as much as 40,000 volts before being punctured. A long cable, however, is likely to contain weak spots, which may be punctured at a much lower voltage. In fact, there are instances where cables have been broken down by a few hundred volts. The cost of making repairs to a cable which has been damaged is large, and it is therefore customary to keep operating voltages down to a conservative value.

A potential of 50 volts is commonly used for operation. Due to the effect of the sending condenser, the strain caused to the cable is somewhat increased, so that the insulation near the end is subject to a maximum strain of about 75 volts. In the center of the cable the maximum strain on insulation is very much lower.

5. *Magnetic Storms.* Fortunately, magnetic storms occur only at comparatively wide intervals, otherwise cable engineering might have developed along entirely different lines. Magnetic storms are ordinarily, if not always caused by conditions on the sun. Slight effects from this source are fairly common, but severe magnetic storms occur only rarely, sometimes years apart. Whenever a severe storm occurs, there are displays of the aurora borealis in the sky, the compass needle is affected, and voltages ranging up to several hundred volts are induced in cables. The voltages alternate from one direction to the other in an irregular manner and at a low speed. The period of the reversal may be a few seconds or it may be as long as a half hour. A severe storm may make cable operation impossible for several hours and its effect may not entirely disappear for three or four days.

THE ARRIVAL CURVE

If a direct-current voltage is suddenly impressed upon a cable grounded at the far end, a current flows into the cable according to the upper curves of Fig. 7. At the distant end of the cable, the current builds up according to the middle curve. The shape of this curve was originally worked out by Lord Kelvin in 1855. The strength of current received through the cable finally reaches a value many times stronger than that necessary to operate the usual receiving apparatus. The rate of increase of current is so slow, extending as it does over several seconds, that rapid signaling with a simple cable circuit is impossible. The various condensers and magnetic shunts introduced in the cable circuit for shaping signals act to remove the greater part of the received current, while retaining the sharp initial rise of current. The result is that the current in the receiving coil is approximately of the shape of the lower curve.

A curve such as one of the lower curves of Fig. 7, which shows the current received over a cable due to a suddenly impressed voltage, is known as an "arrival curve." Any combination of signals may be built up by algebraically adding a succession of arrival curves, in the manner illustrated in Fig. 8.

In studying cable operation, it is convenient to think in terms of the arrival curve. It is essential that the arrival curve be of proper shape, within certain limits, in order that all signal combinations may be legible. In Fig. 9 are shown various shapes of arrival curves, and also the shapes of the first three letters of the alphabet, built up by proper addition of a succession of arrival curves of the shapes given.

The Dot Frequency. By *dot frequency* is meant the normal frequency of operation when a succession of reversals is sent without spaces between them. Thus the letter *a*, consisting of one dot above, and an equal deflection below the zero line, is considered to be one cycle. The letter *c* is considered to be two cycles. In Fig. 9, the base line of each arrival curve is shown divided into equal spaces. Each of these spaces represents the length of one dot, that is, one-half cycle.

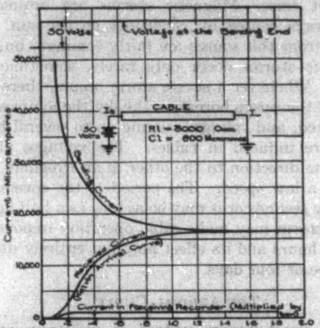

FIG. 7—SENDING AND RECEIVED CURRENT OVER CABLE

A cable such as that previously referred to, with 3000 ohms and 800 microfarads, could be commercially worked at a speed of 54 words per minute, or 324 letters per minute, under favorable conditions. By analyzing the standard cable code, it is found that this is equivalent to an average dot frequency of approximately ten cycles per second.

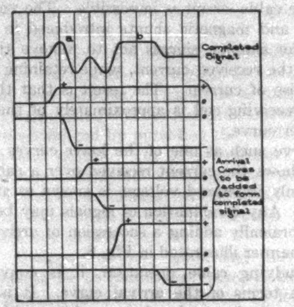

FIG. 8—ADDITION OF ARRIVAL CURVES TO FORM COMPLETED SIGNALS

THEORY OF CABLE OPERATION

The theory to follow is based upon the use of ordinary alternating-current theory. *A knowledge of the behavior of the cable and its associated apparatus under the influence of a sine wave of current throughout the proper range of frequencies, is sufficient to enable the shape of received signals to be predicted.* The action of any equipment may be determined by investigating its behavior through a range of frequencies. The frequencies which must be considered in cable investigations are those from zero frequency to a frequency two or three times the so-called "dot frequency" of operation, as explained later.

The fundamental theory of this method of analysis is developed in the Appendix. It is shown there that in general any transient curve may be considered to be composed of the sum of an infinite number of pure sine waves, of frequencies varying from zero to infinity. Each of these sine waves is attenuated in the cable circuit in accordance with well-known laws. Even the mechanical motion of receiving coils may be approximately or exactly solved by applying methods such as are used in solving alternating-current circuits.

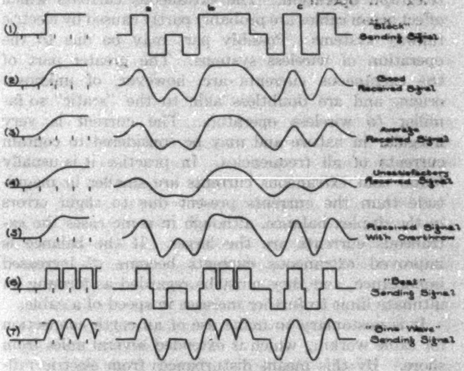

FIG. 9—TYPES OF ARRIVAL CURVES

While this method of analysis is of quite general application, it will be illustrated by applying it to the cable of standard present-day type previously referred to, and to simple apparatus used for operation.

The Frequency Characteristic. This term is used to designate a pair of curves which show how sine wave currents are changed in magnitude and in time lead or lag, by the cable circuit or by a part of the circuit, at various frequencies.

Notation.

E = battery voltage.
E_s = sending voltage as modified by type of signal used.
R = cable resistance per mile (inductance and leakage of cable are ignored).
C = cable capacity per mile.
l = cable length in miles.
f = frequency in cycles per second.

F = dot frequency in cycles per second.

Z_0 = surge impedance of cable = $\sqrt{\dfrac{R}{j\,2\,\pi\,f\,C}}$ [1]

P = complex attentuation constant

= $\sqrt{j\,2\,\pi\,f\,R\,C}$ [1]

I_s = current at sending end of cable.

I_r = current at receiving end of cable.

Z_s = impedance offered to outgoing current by apparatus at sending end.

Z_r = impedance of complete receiving system.

D = deflection of receiving instrument. The maximum deflection (neglecting a momentary overthrow) is taken as unity, the deflection at any frequency being expressed as a fraction of the maximum.

M = magnification of complete receiving set at any frequency = ratio D/I_r.

Solution with Single-Frequency Alternating Current. A standard expression for current received through a cable is the following:

$$I_r = \frac{E_s\,Z_0}{(Z_0^2 + Z_r\,Z_s)\sinh P\,l + (Z_0\,Z_r + Z_0\,Z_s)\cosh P\,l} \tag{1}$$

This may readily be put into the form

$$D = \frac{E_s}{Z_0 + Z_s} \cdot \epsilon^{-Pl} \cdot \frac{2\,Z_0\,M}{Z_0 + Z_r} \cdot \frac{1}{1 - \dfrac{(Z_0 - Z_r)\,(Z_0 - Z_s)}{(Z_0 + Z_r)\,(Z_0 + Z_s)}\,\epsilon^{-2\,Pl}} \tag{2}$$

The first term of the right-hand member of equation (2) gives the current flowing into the cable, as modified by apparatus at the sending end. The second term shows how the current is modified by the cable itself, and the third term shows how the current is modified by the receiving apparatus as a whole. The fourth term takes into account multiple reflections between the ends of the cable. The latter term may for all practical purposes be considered equal to unity, and may be ignored, as it has no effect except at speeds far below the usual signaling speed.

Analyses of Arrival Curves. If a voltage is impressed at the sending end of a shape corresponding to curve 1, Fig. 9, and the cable circuit as a whole, including apparatus, attenuates all frequencies equally, the wave as received at the distant end will be of exactly the same shape. Under these conditions, all signals would be reproduced at the receiving end exactly as they were sent.

If the characteristics of the cable circuit are such that the higher frequencies are lost in transmission, then the tendency is to round off the corners of the wave in a definite manner, so that a more or less rounded signal is the result. Such rounding-off is not objectionable providing it is not carried too far. It becomes then of the utmost importance to determine just what frequencies it is necessary to transmit through the cable in order to obtain a received signal that is sufficiently legible. Since the higher frequencies are most difficult to transmit through the cable, it will be obvious that the ideal shape of arrival curve is one which, while giving good signals, requires the transmission of the smallest possible amount of the higher frequencies. In order to determine what frequencies it is necessary to transmit, a theoretical analysis was made of a large number of possible arrival curves, using methods given in the Appendix, and tests were also made of working cable circuits.

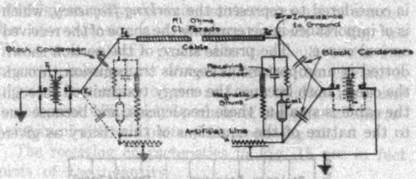

FIG. 10—COMPLETE CABLE CIRCUIT

In order to obtain a received signal which, while somewhat rounded, may be regarded as perfect in shape, it is found necessary to transmit frequencies through a cable up to approximately 2.4 times the dot frequency. Fortunately, however, a received signal of such quality is not necessary for commercial operation, since the rece ving operator becomes so familiar with signals that he is able to read signals which are moderately distorted. It has been found that for recorder reception, with or without a magnifier in circuit, it is necessary to transmit frequencies only up to about 1.5 times the dot frequency in order to obtain a signal which is suitable for traffic.

For relay reception a somewhat better defined signal is necessary, and it is necessary to transmit frequencies up to about 1.65 times the dot frequency. Relay reception is facilitated by permitting a small overthrow of the arrival curve. It can be shown that such an arrival curve can be built up with smaller amounts of the higher frequencies.

Examples of signals which have been chosen to represent the approximate limits of good transmission, for recorder and relay reception respectively, are shown

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[1] In the general case, with inductance L and leakage G present, these become,

$$Z_0 = \sqrt{\frac{R + j\,2\,\pi\,f\,L}{G + j\,2\,\pi\,f\,C}}$$

$$P = \sqrt{(R + j\,2\,\pi\,f\,L)\,(G + j\,2\,\pi\,f\,C)}$$

opposite curves 3 and 5 of Fig. 9.[2] These arrival curves are redrawn to a larger scale in Fig. 11.

In Fig. 12 are shown the frequency characteristics corresponding to the above arrival curves. These characteristics show the approximate deflection and time lag which the receiving instrument must have at any frequency, when a sine wave of voltage is impressed at the sending transmitter. The portion shown solid is considered to represent the *working frequency*, which is of importance in determining the shape of the received arrival curve. The precise shape of the portion shown dotted is unimportant as regards transmission through the cable, both because the energy transmitted through the cable is small at these frequencies, and because due to the nature of the equations of this theory as given in the Appendix, the higher frequencies are of less importance.

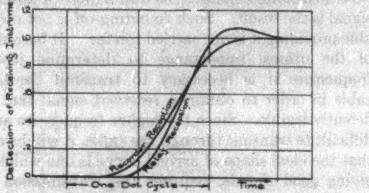

Fig. 11—Ideal Arrival Curves

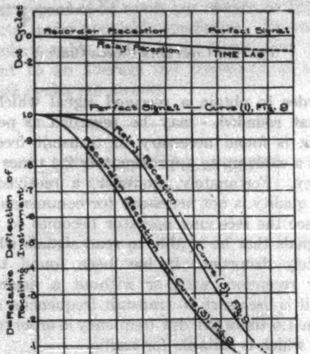

Fig. 12—Ideal Frequency Characteristics of Complete Cable Circuit

It will be recognized that there may be some difference of opinion as to when the received signal is legible. For this reason there is some variation in the frequency limits required for reception by different cable operators. The limits given, however, may be taken to represent average values, and are of the highest importance in studying cable problems.

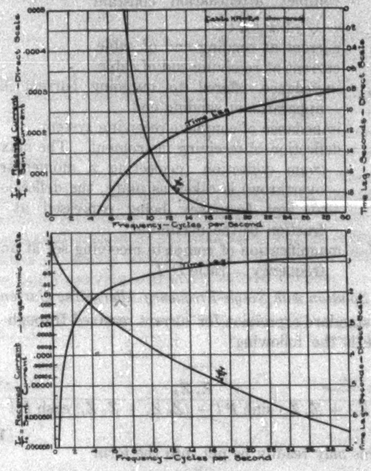

Fig. 13—Frequency Characteristics of Cable

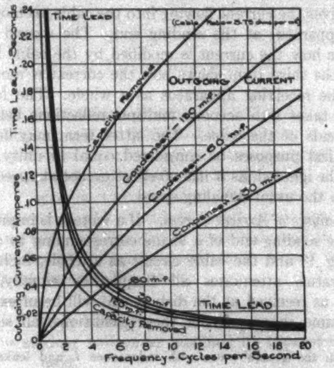

Fig. 14—Frequency Characteristics of Sending Apparatus

Frequency Characteristic of Cable. The frequency characteristic given in the preceding section was the characteristic of the entire cable circuit, from transmitter to recorder, necessary for proper reception. It is now the purpose to determine the separate frequency characteristics of different parts of the system.

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[2] The following table gives the range of frequencies contained in each curve of Fig. 9:

Curve 1, 6 and 7—zero to infinity
" 2—zero to 1.9 times the dot frequency
" 3— " " 1.5 " " " "
" 4— " " 1.1 " " " "
" 5— " " 1.65 " " " "

The frequency characteristic of the cable itself is shown in Fig. 13. This characteristic applies to the cable referred to previously. It is shown plotted both to a logarithmic and to a direct scale. The characteristic was determined by calculating real and imaginary values of the second term of the right-hand member of equation (**2**)

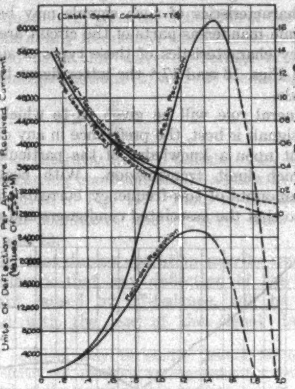

FIG. 15—FREQUENCY CHARACTERISTICS OF COMPLETE RECEIVING SET

Frequency Characteristics of Sending Apparatus. In Fig. 14 are shown frequency characteristics of the current entering the cable, for three different sizes of the condensers at the sending end, and also with the condenser removed. The values in this figure were obtained from the first term of the right-hand member of equation (**2**), the sending voltage being taken at fifty volts.

This figure clearly shows the beneficial effect of the sending condenser in decreasing currents of the lower frequencies. The condenser also reduces, in a less degree, the amount of energy flowing into the cable at higher frequencies—an effect which in itself is undesirable, but which can be compensated for by increasing the sending voltage or the sensitiveness of receiving apparatus.

Frequency Characteristics of Receiving Apparatus. By combining the frequency characteristics shown in Figs. 13 and 14,[3] the frequency characteristic of the current at the receiving end of the cable may be obtained. Now since Fig. 12 shows the frequency characteristics of the cable circuit as a whole, necessary to produce properly shaped signals for reception, it is possible by combining these characteristics with the characteristics referred to above, to obtain characteristics which show the necessary behavior of the receiving set. Such characteristics are shown in Fig. 15.

The characteristics of the receiving set show that this apparatus must be comparatively insensitive to low-frequency currents. It must have its highest sensitivity to currents about 1.3 times the dot frequency for recorder reception, or about 1.45 times the dot frequency for relay reception. The working ranges of frequency, which are important in determining shapes of received signals, are shown as before by solid lines. There are decided advantages from the standpoint of freedom from interference, in having the receiving apparatus insensitive to frequencies higher than the working frequencies.

It is interesting to consider the manner in which the receiving set is made to have characteristics of the shape given. The receiving set is composed of a number of condensers and shunts as shown in Fig. 10. While it is entirely practicable to calculate the frequency characteristic of each part of the circuit, it appears unnecessary to give such calculations here, and a statement will simply be made of the general characteristics of different parts of the receiving set.

The receiving characteristics in Fig. 15 are in fact plots of the quantity

$$\frac{2\,Z_0\,M}{Z_0 + Z_r}$$

taken from equation (**2**). In this quantity, the factor

$$\frac{2\,Z_0}{Z_0 + Z_r}$$

does not greatly vary from unity. The characteristic may therefore be considered to be an approximate plot of the quantity M, which is the ratio of the deflection of the receiving instrument to the current in amperes at the receiving end of the cable. The largest deflection shown is 61,000 units per ampere—that is, full deflection is obtained with 1/61000 ampere = 16 microamperes.

The magnetic shunt, Fig. 10, tends to cause a characteristic which rises with frequency, that is, the shunt tends to absorb currents of lower frequencies, while throwing the higher frequencies into the receiving coil. The condenser in series with the coil has an effect similar to that of the magnetic shunt, and tends to increase further the slope of the characteristic of the complete set.

The block condensers at the receiving end are in effect shunted around the receiving coil and tend to shunt or absorb currents of the higher frequencies. An additional condenser is sometimes placed in shunt with the receiving coil. The values should be such that these condensers mainly absorb only currents above the working frequencies. Such a characteristic may be very beneficial, as it reduces balance troubles and interference from outside sources. The condensers may be semi-resonant with the magnetic shunt, at a frequency between 1.2 and 1.5 times the dot frequency.

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[3] The 60 μf. curve of Fig. 14 was used.

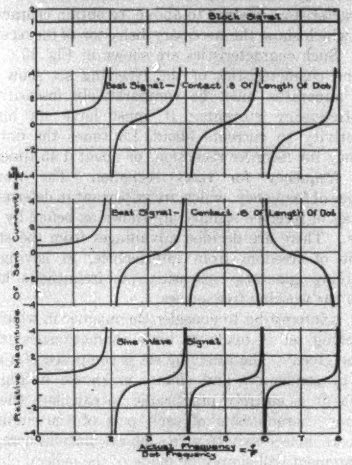

Fig. 16—Frequency Characteristics of Sending Signals

The recording coil has inertia which tends to make it relatively insensitive to the higher frequencies. The coil may be adjusted to have a free period of its own, the period being between 1.2 and 1.5 times the dot frequency.

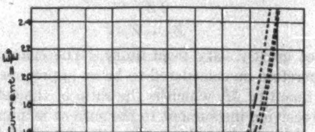

Fig. 17—Frequency Characteristics of Sending Signals

If a magnifier is used of the Heurtley or selenium type, the hot wire of the former, or the selenium cell of the latter, has a certain amount of sluggishness which may have a decidedly beneficial effect in absorbing currents of the higher frequencies.

Frequency Characteristics of Sending Signals. Up to this point it has been assumed that the signal sent is of the so-called "block" type, as shown in curve 1, Fig. 9. There is another type of sending signal which is used to a considerable extent, namely the "beat" type of signal, curve 6, Fig. 9. Still another type has been proposed by Major-General G. O. Squier, namely the sine wave signal, curve 7, Fig. 9.

The characteristics of such signals may be studied in the same manner as parts of the circuit are studied. Frequency characteristics of these types of signals are shown in Figs. 16 and 17,[4] the latter figure being to a larger scale.

No general rule will be given as to which type of sending signals is best, the preference in any case being dependent upon a knowledge of the particular conditions which limit transmission. With beat signals smaller amounts of low-frequency currents are transmitted, so that the associated condensers and magnetic shunt need not absorb as much of such currents. Block signals have advantages from the standpoint of duplex balancing, as will be evident later.

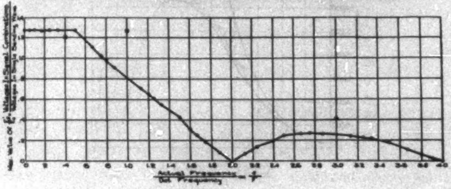

Fig. 18—Analysis of Sending Signal Combinations

The Duplex Balance

Theory. Since cables are usually operated duplex and the balance is often the condition which limits operation of the cable, it is important to consider the theory and practise of balancing.

If there is present a small error in the balance, its effect is in general most severely felt when some irregular combination of signals is sent. In order to analyze this condition, the combination of signals may be considered to recur at regular intervals, and may then be broken up by the standard Fourier method into the sum of a number of separate sine waves. By choosing various possible combinations of signals and analyzing them in this manner, we may determine what the maximum sine wave value of the sending voltage may be at any frequency. This maximum value will be designated E_s'.

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[4] The development of these is given in the Appendix. The curves show only the *transient* characteristics of the signal. In the beat and sine wave signals, there is also a non-transient component which contains frequencies of 2, 4, 6, etc., times the dot frequency. Such frequencies may in general be neglected in studying transmission through the cable, for reasons given previously.

Let it be assumed that the impedance of the cable is Z_0, and that the artificial line is so adjusted that the system would be perfectly balanced if the cable impedance were $Z_0 (1 + \Delta)$ where Δ is a very small quantity. It can then be shown[5] that the deflection of the receiving instrument will be given by the expression

$$D_b = \frac{E_s' \, Z_0 \, M \, \Delta}{(Z_0 + Z_s)\,(Z_0 + Z_r)} \tag{3}$$

Now equation (2) gives the deflection of the receiving instrument at any frequency, when the sending battery is replaced by a sine wave of voltage of value E_s. By combining equations (2) and (3) we have,

$$D_b = 1/2 \cdot \frac{E_s'}{E_s} \cdot \epsilon^{pl} \cdot D \cdot \Delta \tag{4}$$

A plot of the ratio E_s'/E_s, calculated by setting up various recurring combinations of signals as described above, is given in Fig. 18.[6] Plots of the quantity D under ideal conditions, and of $1/\epsilon^{pl}$, were given in Figs. 12 and 13.

In order that duplex operation may be satisfactory, it is necessary that any deflection of the receiving instrument caused by off-balance, will be small as compared with the size of the signal itself. The precise amount permissible depends to some extent upon the individuality of the operator, so that no exact limit can be given. It may, however, be said that an approximate limit for deflection due to off-balance is 0.2 of the size of the dot signal. Now since each of the various combinations of signals contains several different frequencies, the effects of which are aggregated at times, it is necessary to apply a "factor of safety," which will here be assumed equal to 2. Taking these considerations into account, equation (4) may be put into the form

$$1/\Delta = \frac{E_s'}{E_s} \; \frac{D \cdot \epsilon^{pl}}{0.094} \quad \text{for recorder reception.} \tag{5}$$

$$1/\Delta = \frac{E_s'}{E_s} \; \frac{D \cdot \epsilon^{pl}}{0.16} \quad \text{for relay reception.} \tag{6}$$

Plots of values of $1/\Delta$ are given in Fig. 19. This figure shows the approximate degree of accuracy which the balance must possess at all frequencies, in order to permit operation of the cable previously referred to, at a dot frequency of ten cycles per second. It should be noted that the curves in Fig. 19 have been built up on the basis of having apparatus which eliminates the higher unnecessary frequencies. With unfavorable operating apparatus far greater accuracy of the balance may be necessary.

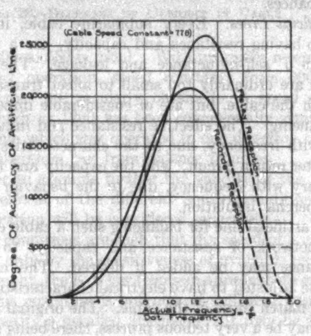

FIG. 19—ACCURACY REQUIREMENTS OF DUPLEX BALANCE

Balance difficulties are an inherent property of a cable system operated duplex, for even if the cable is once balanced correctly, the balance is subject to change due to variations that occur in the temperature of the ocean bottom. In practise it is usually necessary to readjust the balance at least daily, in some cases several times daily. As shown above, a change in the impedance of the cable of one part in 25,000 is sufficient to be important. To maintain a balance correct at one frequency only to this degree of accuracy might not be especially difficult. The chief difficulty is, in fact, the maintenance of a balance correct to the required accuracy throughout a considerable range in frequency.

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[5] This equation may be readily proved for any special terminal circuit, by obtaining an expression for the current in each branch of the circuit when a sending voltage E_s' is impressed at the apex. A general proof may be obtained by breaking the impressed voltage into two parts, of which one part causes a current I_s to flow in line and in artificial line. The remaining part then acts to cause a current I_b, due to off-balance, to flow from the line into the receiving circuit. The deflection is M times I_b. It is assumed throughout that circuit conditions at the two ends of the cable are similar.

[6] As examples of combinations chosen are the following. (1) Reversals; (2) Dot, dash, dash, dot, dash, dash, etc.; (3) Dot, dot, dash, dash, dot, dot, dash, dash, etc. A large number of other combinations was used. The curve in Fig. 18 is, of course, discontinuous. There are two points separate from the curve at $f/F = 1$ and at $f/F = 3$. (Balance disturbances from these particular frequencies are not likely to be more severe than from others, because it happens that these frequencies occur only together, and do not occur in combinations with the numerous other frequencies.) The above signal combinations may be assumed made up of "block" signals, or they may be assumed made up of "beat" or other shaped signals. If the latter, it will be found on trial that the values of E'_s are changed in amount, for any signal combination, by a ratio given by the ordinates of Figs. 16 and 17. But the value of E_s is also changed by the same amount, and the ratio E'_s/E_s is therefore independent of the type of signal. It should not be inferred from this that the type of sending signal has no influence on balance. The actual value of D in equations (4), (5), and (6), may be altered by changing the signal type, which may thus materially influence balance troubles. We are here concerned with the maximum values of the quantities in the equations, and it is not necessary to consider the angle of ϵ^{pl}.

From the theory and curves given above, three important conclusions may be drawn regarding balancing, as follows:

(1) The effect of a given balance error upon the receiving instrument is dependent upon the *actual* shape of the frequency characteristic (Fig. 12) of the entire cable circuit. The actual shape of the characteristic becomes of rapidly increased importance at the higher frequencies.

(2) If there is a certain error in the balance, there can be nothing done *throughout the working range of frequencies*, to decrease its effect upon transmission, by altering the apparatus at either the sending or receiving end, excepting insomuch as the alterations change the shape of the useful transmitted signal.

(3) Any change in the apparatus at either the sending end or the receiving end of the cable, which decreases the magnitude of current transmitted through the cable *at frequencies higher than the working range*, without unduly affecting frequencies within the working range, is a distinct advantage in decreasing balance disturbances.

Artificial Lines. Every submarine cable, in addition to having resistance and capacity, has a certain amount of self-inductance and leakage. The latter factors are ordinarily too small to affect transmission through the cable, but are of considerable importance in balancing. The effective resistance and inductance vary with frequency, due to the characteristics of the sea-water return circuit,[7] and the capacity and leakage also vary with frequency, due to the behavior of the gutta-percha insulation.

The artificial line for balancing such a cable consists of a network of resistance and capacity, to which inductance may be added if desired. The network must be adjusted to have electrical characteristics that closely match those of the cable. The original adjustment may be a very tedious process, there being records of cases where as much as three months' work was done in obtaining a duplex balance for a single cable. Much of the early balancing was done without fully understanding the theory of balancing, and some ingenious appliances to artificial lines were developed by workers in the field, at a time when the electrical properties of the cable itself were incompletely understood. Fortunately, the theory is now better known so that the time required in balancing has been greatly cut down.

Artificial lines of any type are more or less sensitive to temperature changes, and are, therefore, usually placed in heat-insulated cabinets, sometimes located in rooms having special heat-insulated walls. In order to provide for convenient minor daily adjustments, it is customary to provide in addition a few small adjustable condensers and resistances, located near the receiving apparatus, and connected in the artificial line or in the bridge circuit.

The earliest type of artificial line was of the lumped variety, Fig. 20, used by Stearns. This artificial line was not successful, due probably to defects in design and construction.

Shortly afterwards, in 1875, the smooth type of artificial line was patented by Taylor and Muirhead.

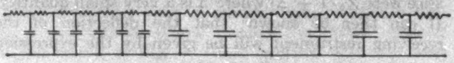

Fig. 20—Stearns Type of Artificial Cable
Capacity and resistance of each section adjustable

In this line (Fig. 21), the resistance of the line is made up of a zig-zag strip of tinfoil. This is insulated from the solid ground sheet of tinfoil by paraffined paper, thus forming the capacity of the line. The line is mounted in wooden boxes, having 10 to 21 microfarads per box, with terminals brought out which divide the line into sections of from one to three microfarads each. This type of line is especially sensitive to temperature changes.

A more recent type of artificial line has been patented by Dearlove. This line is made up of a large number of very small units of resistance and capacity, the latter being from 1/30 to 1/15 microfarad each. Neither the resistance nor the capacity is adjustable. The resistance and capacity are mounted together in boxes, similar to the type previously described.

With either of the types just described, the artificial line must be specially designed and constructed to match the cable with which it will be used, since the constants can be adjusted only in an indirect manner which introduces irregularities in the artificial line that have no duplicate in the cable.

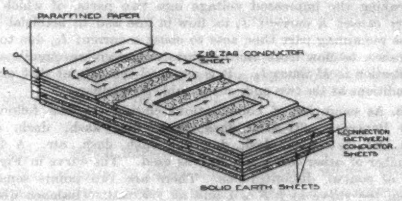

Fig. 21—Diagram of Muirhead Type of Artificial Cable

A new type of artificial line[8] has been developed by the writer, with the object of overcoming the disadvantage of the types previously described. This artificial line is shown diagrammatically in Fig. 22, and contains resistances and condensers in fairly large lumps.

While it might seem that a lumped line of this type could not be made to balance a cable with constants uniformly distributed, the actual condition is that the lumped arrangement is utilized to aid in balancing the inductance of the cable. It may readily be shown that the impedance of such network having a large number of resistances and condensers is

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[7] See J. R. Carson and J. J. Gilbert: "Transmission Characteristics of the Submarine Cable." *Journal of the Franklin Institute*, Dec. 1921.

[8] Patents pending.

$$= \sqrt{\frac{R'}{j\,2\,\pi\,f\,C'} + R'\,R'' + R'^2/4} \qquad (7)$$

The surge impedance of a submarine cable with resistance, capacity and inductance is

$$Z_0 = \sqrt{\frac{R}{j\,2\,\pi\,f\,C} + L/C} \qquad (8)$$

From these it is apparent that a balance which is correct for all frequencies may be obtained if

$$R'/C' = R/C, \quad \text{and} \quad R'\,R'' + R'^2/4 = L/C \qquad (9)$$

An artificial line of this type has the additional advantage that it is readily constructed to be completely adjustable throughout its length. In practise the resistances and condensers are mounted in separate boxes, and the resistance of the line is made continuous with taps brought out at intervals. The resistance steps are small near the head of the line, and become increasingly larger away from the head. For adjustments a movable connector is used which is reliable and convenient to handle, and which does not introduce appreciable contact resistance. It is found that an adequate balance can be obtained with condenser units of two microfarads near the head of the line, and with considerably larger units toward the rear of the line. The resistances in series with the condensers need little if any adjustment, and are only necessary near the head of the line.

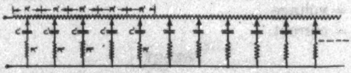

Fig. 22—Adjustable Type of Artificial Line

KELVIN'S *KR* LAW

This law, formulated early in the history of the science, states simply that the operating speed of the usual type of cable is inversely proportional to the product of its capacity times its resistance, the letters "*KR*" being an old symbol for this product. Expressed in another way, the law states that the product of speed times the "*KR*" is a constant. With speed expressed in letters per minute, cable resistance in ohms, and capacity in farads, this product is termed the "speed constant" of the cable, and is widely used.

That the *K R* law is approximately true is immediately evident from the preceding theory [see equation (2)]. The amount of energy which is transmitted through the cable is directly dependent upon the product of frequency times resistance times capacity, and if there is a definite minimum permissible amount of received energy, then there must be a definite value of the above product.

Obviously, the above does not take into account the fact that different conditions may in different cases act to limit the speed of a cable. The "speed constant" is therefore not a definite fixed value, but varies in different cases, and is in fact a measure of the efficiency of operation. With recorder reception a speed constant of 500 to 550 is usual. With magnifier reception and duplex operation, speed constants from 600 to 800 or higher are regularly obtained. A speed constant as high as 1200 has been commercially attained over a cable which was operated in one direction only, and was therefore free from balance troubles.

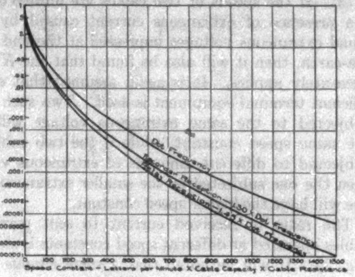

Fig 23—Decrease of Current in Cable

In order to examine further the validity of the *K R* law, the effects of the different limiting conditions to cable operation will be considered separately.

(1) If conditions are such that the speed of a cable is limited only by the sensitiveness of available receiving equipment, the *K R* law forms an approximate guide only. This condition is not now of sufficient importance to justify a detailed discussion. It may be said, however, that of two cables of unequal length a somewhat higher speed constant (although a lower speed) will in general be obtained over the longer cable, for the reason that a given receiving instrument can be adjusted to have higher sensitiveness when used for operation at low speed.

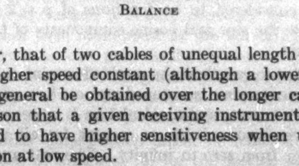

Fig. 24—Relative Accuracy Requirements of Duplex Balance

(2) If the speeds of two cables are limited only by

the duplex balance, and the cables are subjected to the same percentage balance variations and have equally efficient terminal equipment, then the *K R* law is an accurate guide to their relative speeds. This is evident from equations (**5**) or (**6**), for with any given value of f/F, each term of the equation is constant, and the quantity $P\,l$ is therefore constant.

(3) If the speeds of two cables are limited only by the presence of extraneous current caused by small equal extraneous voltages impressed at the end of the sea-earth, then it will also be found that the *K R* law accurately applies. It is again assumed that equally efficient terminal equipment is used. Two such cables subjected to the same extraneous voltage will have the same speed constant, while if the two cables are subjected to different amounts of extraneous voltage, then the one subjected to the smaller extraneous voltage will have the higher speed constant.

The ratio of received current to sent current in cables operated at different speed constants is shown in Fig. 23. It will be noted that a small change in the speed constant requires considerable increase in the sensitiveness of receiving equipment. The approximate degree of accuracy that the duplex balance must possess with different speed constants, assuming favorable terminal apparatus, is shown in Fig. 24.

In conclusion the writer desires to acknowledge the valuable assistance which he has received in the preparation of this paper, from Mr. C. H. Cramer and Mr. W. D. Cannon.

Appendix

In this Appendix is given the fundamental theory of the method of analysis used in the body of the paper. While the general plan has previously been to assume the shape of the received current to be known, and to determine the frequency characteristic from the known current, the method also provides for determining the received current or voltage when the frequency characteristic is known, as shown below. The most useful case is to determine the received current caused by the application of a suddenly impressed steady voltage, yet the method is applicable for determining effects caused by any general transient shape of voltage or current, in cable or other electrical circuits.

The frequency characteristics have previously been considered to be functions of the frequency, and to show the magnitude and the time lead or lag of the wave. In the Appendix the frequency characteristics will be considered to be functions of $p = 2\,\pi\,f$, and will show the sine and cosine components of the wave separately.

In order to calculate the received current or voltage, the transient source is assumed replaced by a continuous sine wave source, and a calculation is in general made of the received voltage or current for all values of frequency from zero to infinity. The real and imaginary components are calculated separately, and are denoted respectively by u and v. A formula for the received voltage or current caused by a suddenly impressed continued voltage is given in equation (**10**).

In difficult cases the necessary integrations are too complicated to be solved analytically, and it is necessary to resort to a graphical or mechanical method of integration. A form of harmonic analyzer is especially applicable.

NOTATION

t = time
p = $2\,\pi \times$ frequency
y = height of transient curve (function of t)
s = sine component of frequency characteristic (function of p)
c = cosine component of frequency characteristic (function of p)
u = real component of received sine wave (function of p)
v = imaginary component of received sine wave (function of p)
j = $\sqrt{-1}$
$a, b, g, k, m, n, A, P, T,$ constants
R = resistance
L = inductance
E = voltage
I = current

THEORY

The method is a development of Fourier's series. Referring to Fig. 25, the Fourier expression for a single valued continuous curve of any shape between the limits of $-\,2\,k$ and $+\,2\,k$ is,

$$y = a_1 \sin \frac{\pi\,t}{2\,k} + a_2 \sin \frac{2\,\pi\,t}{2\,k} + a_3 \sin \frac{3\,\pi\,t}{2\,k} + \ldots$$

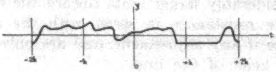

FIG 25

$$+ b_0 + b_1 \cos \frac{\pi\,t}{2\,k} + b_2 \cos \frac{2\,\pi\,t}{2\,k}$$

$$+ b_3 \cos \frac{3\,\pi\,t}{2\,k} + \ldots \qquad (1)$$

A curve such as shown in Fig. 26 may be expressed by the simpler form,

$$y = a_1 \sin \frac{\pi\,t}{2\,k} + a_3 \sin \frac{3\,\pi\,t}{2\,k} + \ldots$$

$$+ b_0 + b_1 \cos \frac{\pi\,t}{2\,k} + b_3 \cos \frac{3\,\pi\,t}{2\,k} + \ldots \qquad (2)$$

$$= \sum_{1,3\ldots}^{\infty} a_m \sin \frac{m\,\pi\,t}{2\,k} + b_0 + \sum_{1,3,\ldots}^{\infty} b_m \cos \frac{m\,\pi\,t}{2\,k} \qquad (3)$$

In Fig. 26, the two halves of the curve are similar in shape, but inverted. The portion between $-k$ and $+k$ is the part in which we are especially interested. The value of k may be made as large as desired, so that in practise any shape of continuous curve may be expressed by (3).

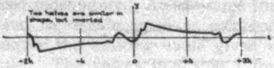

Fig. 26

An additional limitation upon the curve will now be made in order to simplify further the mathematics. It will be assumed that the curve is horizontal, as shown in Fig. 27, excepting for a small portion in the neighborhood of the vertical axis. The value of k will later be assumed increased indefinitely, as in Fig. 28. In the remainder of this theory, it is assumed that the transient under investigation is of the general type shown in Fig. 28. This limitation does not prevent the investigation of those types of transients in which we are interested, as is shown later.

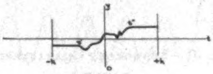

Fig. 27

Referring to equation (3), the value of m takes every odd integer value from one to infinity. By assuming k increased indefinitely, (3) may be replaced by an equation containing integrals, and becomes of the form

$$y = 1/\pi \int_0^\infty s \sin pt \, dp + 1/\pi \int_0^\infty c \cos pt \, dp + b_0, \quad (4)$$

in which $\frac{m\,\pi}{2\,k}$ has been replaced by p, $k\,a_m$ has been replaced by s, and $k\,b_m$ has been replaced by c. The quantities s and c are functions of p, and constitute the *frequency characteristic* referred to previously.

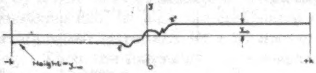

Fig. 28

For each type or shape of transient curve there is a pair of quantities s and c, which correspond to the one transient curve only. The frequency characteristic is independent of the actual value of k, provided that k is large. Equation (4) enables the transient to be determined when the frequency characteristic is known. Equations (8), below, enable the frequency characteristic to be determined when the transient itself is given. Equations (4) and (8) are the fundamental equations of this theory.

To develop the latter equations, we have the well-known equations for determining the constants of Fourier's series,

$$a_m = \frac{1}{2\,k} \int_{-2k}^{2k} y \sin \frac{m\,\pi\,t}{2\,k} \, d\,t$$

$$b_m = \frac{1}{2\,k} \int_{-2k}^{2k} y \cos \frac{m\,\pi\,t}{2\,k} \, d\,t \quad (5)$$

$$b_0 = \frac{1}{4\,k} \int_{-2k}^{2k} y \, d\,t$$

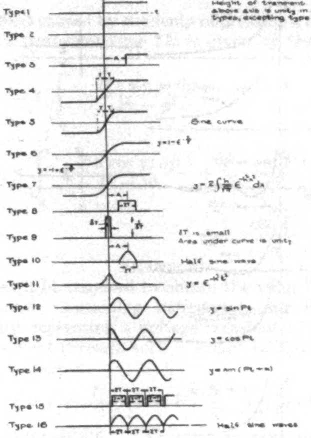
y
Note:
Height of transient above axis is unity in all types, excepting type 9.
Type 1
t
Type 2
Type 3
A
Type 4
T
T
Type 5
T
T
Sine curve
Type 6
y = 1 − ε^{-t}
y = −1 + ε^{t}
Type 7
y = 2∫ h/√π ε^{-h²x²} dx
Type 8
A
2T
Type 9
δT
δT
δT is small
Area under curve is unity
Type 10
A
2T
Half sine wave
Type 11
y = ε^{-h²t²}
Type 12
y = sin Pt
Type 13
y = cos Pt
Type 14
y = sin (Pt + α)
Type 15
2T
2T
2T
Type 16
2T
2T
2T
Half sine waves

Fig. 29—Transient Types

Now since we are considering only odd harmonics, the first of these may be written

$$a_m = 1/k \int_{-k}^{k} y \sin \frac{m\,\pi\,t}{2\,k} \, d\,t \quad (6)$$

In evaluating the limits, it will be noted that the sine is at its highest or at its lowest value at each limit. It is not necessary to carry the limits to the values of $-k$ or $+k$; instead it is only necessary to begin the integration from some point at the left of t', Fig. 28, and carry it to some point to the right of t''—providing that in each case the integration is stopped at a point where the sine is at its maximum or at its minimum, *i. e.*, at a point where the cosine is zero.

A similar simplification might be made directly of the second of equations (5) for the special case where $b_0 = O$. In the case where $b_0 \neq O$, the case is less simple. It may, however, be shown that in general, when k is large

$$b_m = 1/k \int_{-k+k/m}^{k-k/m} y \cos \frac{m \pi t}{2 k} \, d t \qquad (7)$$

At each of these limits the sine is zero, and it is again necessary only to carry the integration from some point at the left of t', to some point at the right of t''. As k is increased indefinitely, the above equations take the form below, where substitutions as before have been made

$$\left.\begin{aligned} s &= \int y \sin pt \; dt \text{ between limits where } \cos p\, t = O, \\ c &= \int y \cos pt \; dt \text{ between limits where } \sin p\, t = O, \end{aligned}\right\} \qquad (8)$$

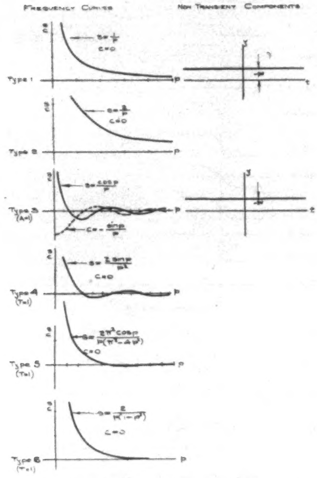

FIG. 30—FREQUENCY CHARACTERISTICS

each integration to be carried *through* the transient.

$$b_0 = \frac{y_{-\infty} + y_{\infty}}{2}$$

In Fig. 29 are shown examples of a number of types of transients, and in Table I are given formulas for the frequency characteristics for the various types. These formulas were calculated with the aid of equations (8). If the values given in Table I are substituted in equation (4) and the integration is carried out, the original transient will be obtained. Plots of a number of the frequency characteristics are given in Figs. 30 and 31.[9]

Further explanation is necessary in connection with transient types 12 to 16 inclusive. In calculating the frequency curve of type 12, the transient is assumed to be built up as shown in Fig. 32. The upper part is

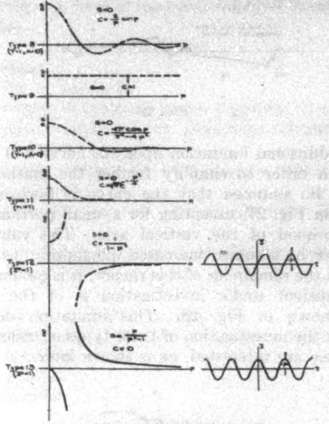

FIG. 31—FREQUENCY CHARACTERISTICS

TABLE I
CONSTANTS OF FREQUENCY CHARACTERISTICS FOR VARIOUS TRANSIENTS

Transient Type	s = sine component	c = cosine component	Non-transient component
1	$1/p$	0	1/2
2	$2/p$	0	0
3	$(1/p) \cos p\, A$	$-(1/p) \sin p\, A$	1/2
4	$\frac{2 \sin p\, T}{p^2\, T}$	0	0
5	$\frac{2\, \pi^2 \cos p\, T}{p\, (\pi^2 - 4\, p^2\, T^2)}$	0	0
6	$\frac{2}{p\, (1 + p^2\, T^2)}$	0	0
7	$(2/p)\, \epsilon^{-p^2/4h^2}$	0	0
8	$\frac{2 \sin p\, T}{p} \sin p\, A$	$\frac{2 \sin p\, T}{p} \cos p\, A$	0
9	0	1	0
10	$\frac{4\, \pi\, T \cos p\, T}{\pi^2 - 4\, p^2\, T^2} \sin p\, A$	$\frac{4\, \pi\, T \cos p\, T}{\pi^2 - 4\, p^2\, T^2} \cos p\, A$	0
11	0	$(\sqrt{\pi}/h)\, \epsilon^{-p^2/4h^2}$	0
12	0	$\frac{P}{P^2 - p^2}$	$(1/2) \sin P\, t$
13	$\frac{p}{p^2 - P^2}$	0	$(1/2) \cos P\, t$
14	$\frac{p \sin \alpha}{p^2 - P^2}$	$\frac{P \cos \alpha}{P^2 - p^2}$	$(1/2) \sin (P\, t + \alpha)$
15	$\frac{\sin n\, p\, T}{p \sin p\, T}$	0	Continuous, similar in form to right-hand part of original, and half the height.
16	$\frac{2\, \pi\, T \cot p\, T}{\pi^2 - 4\, p^2\, T^2}$	0	

---

[9] It should be noted that the characteristics shown in Figs. 12, 16 and 17 of the body of the paper are comparative rather than absolute characteristics. They show the ratio at each frequency of the characteristics of the transient under consideration, to the characteristic of transient type 1.

the transient component; the lower part is a non-transient component consisting of a continuous sine wave of half amplitude. The height of the transient component is assumed to be a double exponential curve as shown. The frequency characteristic of this transient is first calculated, after which the value of g is increased indefinitely. At the same time, g must be considered to remain small as compared with k. In this manner the limiting value given in Table I was obtained. The values in Table I for transient types 13, 14, 15, and 16 were calculated in a similar manner. The non-transient components of types 15 and 16 are themselves irregular in shape, and may be broken up by the standard Fourier method into the sum of a series of continuous sine waves. Thus the non-transient component of type 15 is equivalent to

$$n/2 - \frac{\sin n\pi}{\pi} \cos \frac{\pi t}{T} + \frac{\sin 2 n \pi}{2 \pi} \cos \frac{2 \pi t}{T} - \ldots$$

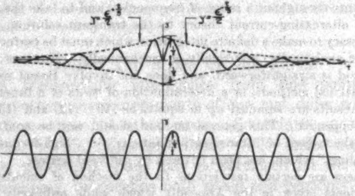

FIG. 32—DEVELOPMENT OF TRANSIENT TYPE 12

APPLICATION TO ELECTRICAL PROBLEMS

Referring now particularly to transient type 1, the preceding theory shows that it may be regarded as the sum of an infinite number of sine waves, of heights equal to $1/p$, added to a non-transient component of height $1/2$. The sine waves are individually attenuated in the electrical circuit in a manner which can be calculated by ordinary alternating-current theory, thus obtaining the frequency characteristic for the resultant effect at the receiving end. Then from equation (4) the shape of the received current is obtained.

Let it now be assumed that the transient source is replaced by a sine wave of voltage of frequency $p/2\pi$. At the receiving end, let u be the component in phase with the impressed wave, and let v be the component at 90 deg. Then the frequency characteristic of the received current will be

$$\left.\begin{aligned} s' &= u/p \\ c' &= v/p \end{aligned}\right\} \qquad (9)$$

Substituting in equation (4), we have the formula for the received current caused by an initial transient of type 1

$$y = 1/\pi \int_0^\infty \frac{u}{p} \sin pt\, dp + 1/\pi \int_0^\infty \frac{v}{p} \cos pt\, dp + u_0/2 \qquad (10)$$

The effect of the non-transient component of the initial transient has been calculated separately, and included in the formula.

In the general case, applicable to any initial type of transient, let s and c represent the initial frequency characteristic. Then the characteristic of the resultant transient will be

$$\left.\begin{aligned} s' &= s\,u - c\,v \\ c' &= c\,u + s\,v \end{aligned}\right\} \qquad (11)$$

Substituting in equation (4), we have the formula for the resultant transient caused by any initial type of transient

$$y = 1/\pi \int_0^\infty (s\,u - c\,v) \sin pt\, dp + 1/\pi \int_0^\infty (c\,u + s\,v) \cos pt\, dp \qquad (12)$$

If the initial transient is composed, in part, of a non-transient component, the effect of the latter must be calculated separately, and added to the result of equation (12).

The effect caused by suddenly impressing a continued sine wave (transient type 12) is given by the formu

$$y = -1/\pi \int_0^\infty \frac{P\,v \sin pt\, dp}{P^2 - p^2} + 1/\pi \int_0^\infty \frac{P\,u \cos pt\, dp}{P^2 - p^2} + u_P \frac{\sin P\,t}{2} + v_P \frac{\cos P\,t}{2} \qquad (13)$$

EXAMPLES

1. Let it be required to obtain the value of current in a circuit containing inductance and resistance, caused by impressing a voltage transient of type 1.

The current through such a circuit caused by a sine wave of voltage is

$$I = \frac{E}{R + j\,p\,L} = E\,\frac{R - j\,p\,L}{R^2 + p^2 L^2} \qquad (14)$$

From this we obtain

$$u = \frac{R\,E}{R^2 + p^2 L^2}, \quad v = \frac{-\,p\,L\,E}{R^2 + p^2 L^2}, \quad u_0 = E/R \qquad (15)$$

Substituting in equation (10) gives

$$y = 1/\pi \int_0^\infty \frac{R\,E}{p\,R^2 + p^3 L^2} \sin pt\, dp - 1/\pi \int_0^\infty \frac{L\,E}{R^2 + p^2 L^2} \cos p\,t\,d\,p + \frac{E}{2\,R} \qquad (16)$$

$$= \frac{E}{2\,R}\left(1 - \epsilon^{-Rt/L}\right) - \frac{E}{2\,R}\,\epsilon^{-Rt/L} + \frac{E}{2\,R} \qquad (17)$$

$$= E/R\left(1 - \epsilon^{-Rt/L}\right) \qquad (18)$$

Equation (17) was obtained with the aid of a table of definite integrals.

2. The current through an inductance and resistance in series, caused by suddenly impressing a continued sine wave of voltage may be obtained by substituting

in equation (13) the values of u and v from equation (15). The result is

$$I = \frac{E}{R^2 + P^2 L^2} \left(P\, L\, \epsilon^{-Rt/L} + R \sin P\, t - P\, L \cos P\, t \right) \qquad (19)$$

Discussion

M. Sasuly (Communicated after adjournment): In regard to the theory of operation of cables as given in the paper, some qualifying remarks may be appropriate. The statement of the mathematical basis on which the character of signals can be predicted (p. 124) is likely to be misinterpreted. It implies that the mathematics of ordinary a-c. theory alone suffices for the determination of the "transient" as well as the "steady state" characteristics of cable and other circuits. This is correct only in the broad sense that the "transient" solution can be made to depend on the "steady state," or "periodic" solution because both are fundamentally of the same mathematical type, the general exponential function. But it is not to be inferred that the one solution can be derived from the other merely by the processes of ordinary a-c. mathematics. Also it must be noted that the identity in type of the two solutions is limited by certain conditions. These involve considerations of the invariability of the circuit "constants" with current and voltage, the linearity of the differential equations, and the "boundary" conditions applying in the given problem. The scope and importance of these restrictions must not be overlooked. In many practical problems they inevitably introduce considerable mathematical complexity.

The possibility of deriving the "telegraphy" solution of the cable problem directly from the a-c. solution has been a matter of controversy among a number of cable engineers. The issue does not concern merely the question of mathematical method. It is fundamental in the very practical problem of improved signalling through ocean cables by means of high-frequency currents. (Cf. Wagner, "E. T. Z." 1910, p. 163; 1912, p. 1289. Malcolm, Theory of the Submarine Telephone and Telegraph Cable, 1917, pp. 248-251). Consequently it is appropriate to call attention to what is perhaps the essence of the theoretical aspects of the problem.

Under the restrictions referred to previously the "transient" and "periodic" terms constitute the *general* solution. This is composed of a sum of terms of the type of the *particular* solution, the latter corresponding to the "periodic" solution. This fact is seen with little difficulty in the Fourier integral solution of the cable problem, first given by Kelvin about 1854 (Math. and Phys. Papers, II, pp. 48-49), and treated by a number of subsequent writers, with particular concreteness by Heaviside (*e. g.*, Electromagnetic Theory, II, p. 125 (1895)), Poincare (Théorie de la Propagation de la Chaleur, 1895, p. 134; L' Eclairage Electrique, 40, p. 162, 1904), and Wagner ("E. T. Z.," l. c.; Mitteil, Teleg. Vers., V-VI, 1909-1912). The applicability of the Fourier integral solution to circuit networks has been shown by several writers, especially by Wagner (*Archiv. f. Electrotechnik*, 4, p. 162, 1916), Carson (TRANS. A. I. E. E., 38, p. 359, 1919), and Fry (*Phys. Rev.*, 14, p. 118, 1919); also by Pomey (*Revue Gen. de l'Elec.*, 5, p. 204, 1919). In the solution of cable and network problems by Heaviside's Expansion Theorem (l. c., p. 127), the correspondence of the "transient" and "periodic" terms to the constituents of the general solution is no longer apparent. But the correspondence has been explicitly established in the very lucid and direct analytical proof of the Expansion Theorem given by Carson (Phys. Rev., 10, p. 217, 1917).

It is true then that the general solution of ordinary circuit problems can be formally derived from the same type as the a-c. solution. But this fact must not lead to under-estimating the complexity of the process of actually constructing the solution. The use of integral equations, Bessel series, (*e. g.*, Carson, Fry, l. c.) and other advanced mathematical processes is not merely a matter of elegance. Advanced methods are unavoidable in all but very simple and certain special types of circuit problems. Moreover, certain important aspects of the solution are entirely outside the scope of ordinary a-c. methods. These relate to the properties of the *indicial impedance function* (Cf. Carson, l. c.) associated with a circuit system. The roots of this function determine the "natural modes of motion" of the system. A study of these would appear not only to facilitate the solution of given circuits, but also to admit the possibility of designing circuits of predetermined characteristics.

J. W. Milnor: The foregoing discussion indicates that the scope of the paper has been somewhat misunderstood by the writer of the preceding communication, and it may be misunderstood by others. An original method of calculating transients is developed in the Appendix, and it is clearly shown that a transient may be directly determined from a knowledge of the behavior with continued sine wave alternating currents, of the electrical circuit under investigation. The amount of labor involved in the solution is of course by no means nil, since it is necessary to know the behavior of the circuit with alternating currents throughout a range of frequencies; and to take the step from alternating-current theory to the transient solution, it is necessary to make a definite integration which must be performed either analytically, graphically or mechanically. However, the method is straightforward, and does not involve Bessel series, operational methods, or a determination of roots of a function. The results are summed up in equations (10), (12) and (13) of the Appendix. This general method should not be confused with the subject of "transient oscillations" or "high-frequency signaling," which has been covered by different writers.

There are certain restrictions to the method of calculating transients given in the Appendix which while ordinarily not important, should perhaps be specifically mentioned. It is assumed throughout the mathematics that the circuit parameters are invariable with current and voltage,—although it is permissible that they might change with frequency. If the method is used in the solution of a circuit (of academic interest only) which contains no resistance, misleading results will in general be obtained. This condition follows from the fact that the method of development assumes that the quantity k although large, is finite. It is possible to apply the method for solving electrical circuits containing inductance and capacity only, by taking certain precautions, although it appears inadvisable to discuss such considerations here because of their complication. There is a slight omission relative to equation (7) of the Appendix; it should have been stated that this equation is valid *for values of m greater than one*, when k is large.

The suggestion has been previously made at different times that there might be some direct relation between the "telegraph" solution of the cable problem and the alternating-current solution or that it might be possible to derive one from the other. As far as the author knows, however, this is the first time that a mathematical justification for such a relationship has been published.

While the use of this method for calculating general transient effects in an electric circuit involves the performance of an integration,—such an integration may usually be avoided in investigations of ocean cable lines and apparatus. This simplification is made possible by the expedient of determining once for all what *frequency characteristic* a cable circuit must have in order to transmit satisfactory signals. Examples of such frequency characteristics are shown in Fig. 12 of the paper. A certain degree of variation from these is of course possible in practise, since a certain amount of variation in the shape of received signals is permissible. The behavior of an ocean cable or of its apparatus may therefore be directly determined by investigating its behavior with alternating currents,— *i. e.*, its frequency characteristic,— throughout the range of frequency from zero to about twice the dot frequency.

Printing Telegraph Systems Applied to Message Traffic Handling

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***Review of the Subject.**—Ever since the building of the first practical automatic telegraph instruments by Vail in America in 1837, and Wheatstone in England in 1841, an ever-increasing amount of the world's high-speed communication has been carried on by the printing telegraph. While these early machines were built primarily for the use of the European Government Telegraphs or the large American telegraph companies, the developments of the last few years have produced an instrument which is a practical working tool for the service of modern commercial and industrial enterprises.*

This paper discusses some of the economic principles which determine the applicability of the automatic printing telegraph to present-day communication problems. Examples are given of the application of this type of apparatus to modern business conditions and the fundamental fact is demonstrated that whenever speed is essential in communication, consideration should be given to the automatic printing telegraph.

The discussion is limited to those forms of light traffic load printing telegraph systems which have been developed particularly for linking together the departments of the factory, the terminal points of the railroad, the branches of the banking, the brokerage or the selling organization or the units of any other large corporation.

A description is then given of the principle of operation of three such systems, somewhat in detail, as there is very little literature on the subject.

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Object and Scope of the Paper. (430 w.)
Applications of Printing Telegraph Equipment to Commercial Conditions. (640 w.)
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Morkrum "Green Code" System. (2400 w.)
Western Electric "Start Stop" System. (1530 w.)
Kleinschmidt System. (1860 w.)

OBJECT AND SCOPE OF THE PAPER

In transmitting intelligence from one point to another, the requirements of one case differ widely from those of other cases. Sometimes speed of service is the important item, while under certain other conditions speed may be sacrificed for the sake of economy, or perhaps both speed and economy may have to be sacrificed for some other consideration—for instance, the transmission of original documents.

To meet the needs of these different problems, various types of communication systems are now in operation and it is becoming more and more of a problem to choose the system that will best meet the requirements of a given case. The business executive instinctively turns to the systems he is used to, and in many instances does not take the time to find out what other methods of communication are available. Too often a messenger service is used where mechanical conveyors of some kind should be in operation, or additional telephones are pressed into service where a printing telegraph system might be installed to advantage. Perhaps one of the most direct causes of this condition is a lack of literature on the subject.

It is the object of this paper, therefore, to point out very briefly some of the advantages of a branch of the communication art which is not very well-known to the average business man or industrial plant engineer and to describe briefly the operation of a few systems in this class.

The systems referred to are automatic printing telegraph systems. These may be divided into two classes:

1. Heavy traffic load systems.
2. Light traffic load systems.

Where the traffic load is approximately 80 words per minute or over, the volume may be handled with heavy traffic load systems. Smaller loads do not, as a rule, warrant the installation of an elaborate heavy traffic load system, but may best be handled with light traffic load systems. Of course, such conditions as fluctuations in traffic, speed of service or other considerations may justify the installation of a heavy traffic load system in cases where the average traffic load is less than 80 words per minute, for instance, where the traffic often fluctuates far above normal and where speed of service is important. For a general discussion, however, the above division may be taken as applying to a majority of cases.

Heavy traffic load systems have been described in various other papers[1] presented before the Institute but very little mention has been made of the light traffic load system. The following discussion will therefore be limited to three light traffic load systems developed within the last five or six years, namely:

1. The Morkrum "green code" system.
2. The Western Electric "start stop" system.
3. The Kleinschmidt system.

APPLICATIONS OF PRINTING TELEGRAPH EQUIPMENT TO COMMERCIAL CONDITIONS

The three most important savings effected with printing telegraph systems are savings of time, line wire and labor.

The distance between the sending and receiving station does not necessarily have to be as great for the sake of economy, as is often assumed. A printing telegraph system will often pay for itself by the saving of time alone. Take, for instance, a concern where orders are received at a central point, to be filled, part at one department and part at other departments in the same plant. Ordinarily such orders are sent to the first de-

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Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

[1] John H. Bell, "Printing Telegraph Systems." A. I. E. E. TRANS. Vol. XXXIX, Part 2, 1920.

partment where certain items are placed on a truck together with the orders. The truck is then sent to the next point, where additions are made, and so on until the truck passes through all stations involved. This method requires a considerable amount of time which may be saved by using a printing telegraph system. If a receiving set is installed in each department, that part of an order which applies to the first department may be sent by wire to the first department, and that part which applies to the second department may be sent to the second department, etc. All this may be done automatically while making out the invoice. In one operation, therefore, the invoice is made out and the order is sent to the proper sections of the plant. All departments receive their parts of the order at practically the same time, and each may therefore start work immediately without having to wait for the others. The items are then brought together in the shipping room where they are checked against the original order and sent out. This is one instance where the saving of valuable time justifies the installation of a light traffic load printing telegraph system.

To illustrate a condition where line wire may be saved, we may assume a problem where there is a need for rapid transmission of a fairly large volume of traffic from New York to Chicago. Let us consider that speed is an important factor, and that, during the busy hours, the traffic load is over 40 words per minute. If Morse operators were placed at each point, an average of between 30 and 40 words per minute would be the most that could be handled, and to handle the traffic two line wires would have to be leased. The cost of the wires with two Morse operators at each end would be approximately as follows:

Two leased wires (approximately)	$40,000	per year
Four Morse operators at $1800 per year	7,200	“ “
	$47,200	“ “

The installation of a light traffic load system makes the second line wire unnecessary. The annual charges under this arrangement would be approximately as follows:

One Leased wire (approximately)	$20,000	per year
Two Operators at $1200 per year	2,400	“ “
*Two Maintenance men at $1800 per year	3,600	“ “
Annual charges on equipment figuring a depreciation over a period of 8 years, interest, taxes, administration and repair parts (approximately)	1,000	“ “
	$27,000	“ “

By using automatic equipment, the speed may be very materially increased at a saving of approximately $20,000 per year over what it would cost to increase the speed by adding additional Morse operators. This is an instance where a saving of line wire more than justifies the installation of a light traffic load printing telegraph system.

Perhaps the best illustration of how a saving of labor can be effected, by the installation of automatic equipment, is the case of press associations. At one time a well-known press association employed as many as 100 messengers to deliver news to various newspapers scattered throughout a city. Light traffic load printing telegraph systems are now giving these papers far better news service, and, by means of periodic inspections, just a few maintenance men keep the equipment in order. At each newspaper office a receiving set is installed, and one transmitting set at the central bureau sends news to all of the newspapers simultaneously. The editors at the various newspapers tear off the printed copy from time to time but, as paper is fed into the printers automatically, no other attention is necessary.

These are only a few of the cases where automatic equipment may be used to advantage. Many others might be mentioned. Line wire plays but a small part in the first example, and in the second example this system of communication will still prove advantageous even if no saving in labor is shown. In all three cases, however, speed is essential and automatic equipment offers a promising solution of the problem.

The system chosen must be capable of operating at rates of speed slightly higher than that required for handling the average traffic load. At first glance it might appear that to increase the speed of a set above the point where it can handle the traffic under normal conditions would be destructive to the machines. Such is not the case, however. With equipment designed for a range of between 40 and 80 words per minute, the wear is the same for every 1000 words printed, no matter whether that 1000 words is printed at a speed of 40 words per minute or 80 words per minute. On long or poor lines, speed is limited by the carrying capacity of the line, but for shorter distances the speed should be regulated, not from the standpoint of wear on the machines, but in accordance with the traffic load. It has even been found practical to speed up above the sending capacity of one operator and to employ two operators at the sending station during the busy hours.

Methods used in Common by Systems to be Described

All three of the systems to be described make use of the following basic methods:

Messages are first prepared as perforations in a paper tape by typists familiar with a standard typewriter keyboard and the tape is then fed through a

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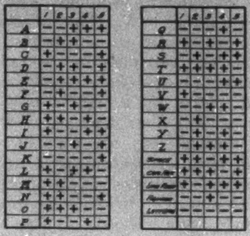
*This figure is kept high for purposes of illustration. A still greater saving would be shown in an actual case, as the maintenance men would either be free most of the day to do other work, or would act as operators, thus wiping out the $2400 operator charge.

transmitter which translates the perforations into line signals and steps the tape forward one character at a time. At the other end of the wire the message is automatically received on a printer in page form.

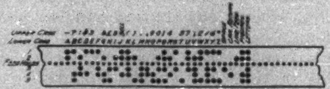
Each system employs a different type of perforator but the perforated tape prepared by any one of them may be used on any of the three systems and also on the multiplex system used by the Western Union Telegraph Company.[2] Likewise each system employs a different type of printer but certain standards are adhered to so that any one of them may be used interchangeably with the printers used in the multiplex system.[2]



	1	2	3	4	5
A	−	−	+	+	+
B	−	+	+	−	−
C	+	−	−	−	+
D	−	+	+	−	+
E	−	+	+	+	+
F	−	+	−	−	+
G	+	−	+	−	−
H	+	+	−	+	−
I	+	−	−	+	+
J	−	−	+	−	+
K	−	−	−	−	+
L	+	−	+	+	−
M	+	+	−	−	−
N	+	+	−	−	+
O	+	+	+	−	−
P	+	−	−	+	−

	1	2	3	4	5
Q	−	−	−	+	−
R	+	−	+	−	+
S	−	+	−	+	+
T	+	+	+	+	−
U	−	−	−	+	+
V	+	−	−	−	−
W	−	−	+	+	−
X	−	+	−	−	−
Y	−	+	−	+	−
Z	−	+	+	+	−
Space	+	+	−	+	+
Car. Ret.	+	+	+	−	+
Line Feed	+	−	+	+	+
Figures	−	−	+	−	−
Letters	−	−	−	−	−

Five-unit code.



Specimen of tape with all characters perforated.

FIG. 1—COMBINATIONS OF POSITIVE AND NEGATIVE IMPULSES REPRESENTING THE DIFFERENT CHARACTERS

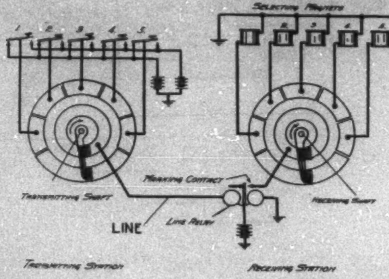


FIG. 2—SCHEMATIC WIRING DIAGRAM OF TRANSMITTING AND RECEIVING APPARATUS

A five-unit code provides 32 combinations of positive and negative impulses as in the multiplex system. These impulses are used to operate five selecting magnets in the printer. For every character selected, one or more of the selecting magnets is operated. This makes it possible to select any one of the 26 letters of the alphabet or any one of the functions such as "space," "carriage return," "line feed," "figure shift," or "letter shift." Counting both the upper and the lower case positions, 52 letters, numbers or other characters are possible. Fig. 1 shows the various combinations of positive and negative impulses that represent each of the different characters.

Motor-driven distributors are employed at both the sending and the receiving stations to transmit the line signals from the sending station at a uniform rate of speed and to receive and interpret these signals at the receiving station. The speed of the motors at each end of the line is maintained uniform by governors.

Fig. 2 is a schematic wiring diagram showing the principle involved in sending and receiving.

The speed at which signals are sent over the line depends on the speed of the transmitting shaft at the sending end. As the line relay at the receiving end operates in accordance with these signals, in order to select any one of the five selecting magnets in the printer, the receiving brush arm must pass over the corresponding receiving segment at the same time that a marking impulse is sent over the line and the line relay tongue is resting against its marking contact.

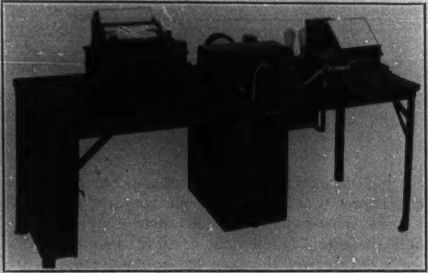


FIG. 3—MORKRUM TERMINAL SET

When the transmitting station stops sending, the receiving brush arm is held stationary by a magnet. At the beginning of each set of signals, a start impulse precedes the first selecting impulse and operates this magnet thereby releasing the receiving brush arm. The five selecting impulses follow and the proper selecting magnets are operated successively as the brushes pass over the receiving segments.

These fundamental features apply to all three systems but the method by which line signals are transmitted from the sending station and interpreted at the receiving end is quite different in each system.

MORKRUM "GREEN CODE" SYSTEM

Fig. 3 shows a Morkrum terminal set. The perforator is shown at the right and the printer at the left with the transmitter and distributor between them.

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[2] John H. Bell "Printing Telegraph Systems," loc. cit.

Transmission. Fig. 4 is a schematic wiring diagram of the circuits involved in transmitting signals over the line.

The tape that is prepared by the perforator is fed through the transmitter and is stepped forward once for each revolution of the transmitting brush arm, Fig. 4, in the distributor. Fig. 5 shows the tape-feeding mechanism. When the contact *A B*, in the distributor, is closed, the transmitter magnet moves lever *A C* clockwise about its pivot *A D* and feeds the tape forward. When the transmitter magnet is de-energized it allows the tape pin contact levers *A E* to move counter-clockwise about their pivot point *A D* until the pins *A F* reach the level of the tape. If a pin is blocked by the tape the contact tongue *A G* remains against its spacing contact. If the perforations in the tape permit a pin to go through the tape, however, the corresponding contact tongue *A G* moves over against its marking contact. There are five pins *A F* and five contact tongues *A G* and each contact tongue is connected to a segment on the transmitting commutator. Consequently when the transmitter magnet is de-energized each segment will be connected to marking or spacing battery according to the perforations in the tape. Segment *A H* is permanently connected to marking battery and segment *A J* is permanently connected to spacing battery. As the transmitting shaft *A A* revolves, the brush first sends a spacing signal which is called the start impulse and then the selecting impulses in accordance with the code combination set up in the transmitter.

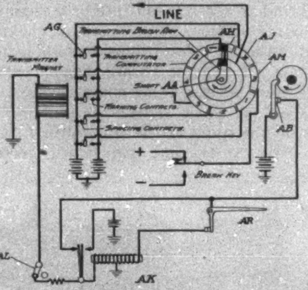

FIG. 4—SCHEMATIC WIRING DIAGRAM OF TRANSMITTING CIRCUITS

The speed may be set so that transmission is carried on at any desired rate from 40 to 65 words per minute.

For every revolution of the transmitting shaft, eight impulses are sent to the receiving station. Two are for synchronizing purposes, one is for sending a bell signal to the distant station without interfering with the message being transmitted, and five are for selecting purposes. Communication is therefore carried on at a line frequency of eight units or 4 cycles per character. Sixty words per minute represents a line frequency of 24 cycles per second.

The transmitting shaft is not stopped after each revolution but continues to revolve until transmission is stopped by the raising of the arm *A R*. Normally when the transmitter cam contacts *A B* are closed, current flows through both windings of the differentially wound auto-stop relay *A K*. The transmitter magnet is therefore operated but as the current flows through the auto-stop relay windings in opposite directions, the latter will not be operated. If, however, the auto-stop arm *A R* is lifted and the transmitter cam contacts closed, current will flow through the transmitter magnet and through only one winding of the relay. This operates both the transmitter magnet and the relay— the relay locking itself in the operated position. The transmitter magnet remains energized until the auto-stop arm is again lowered. During this time the pins are held down and transmission of code combinations is stopped, but the transmitting brushes continue to revolve, sending out starting impulses once every revolution.

If for any reason, it is desired to repeat a character a number of times the switch *A L* may be opened, thereby opening the circuit to the transmitter magnet and allowing the tape to remain stationary with the proper marking and spacing battery combination set up at contact tongues *A G*. Inasmuch as the tape is not stepped forward, the same character is sent over and over again as long as the switch *A L* remains open and the brush arm continues to revolve.

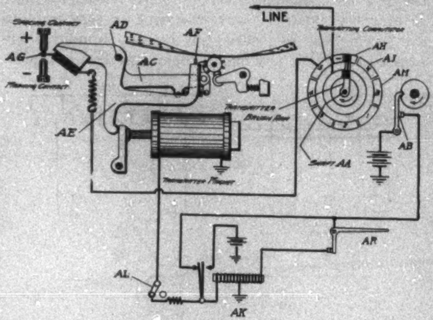

FIG. 5—TAPE-FEEDING MECHANISM

In order to signal quickly to the distant station an extra segment *A M* (Fig. 4) is provided on the transmitting commutator. When the break key is held down, marking battery is connected to the segment *A M* and a marking impulse is sent over the line immediately after the start impulse. This impulse operates a bell at the receiving station in a manner which will be described later.

Reception. Fig. 6 shows the manner in which the receiving units are connected electrically.

The brush arm $A\,N$ is mounted on a sleeve together with the start magnet cam $A\,S$ the break circuit cam $A\,P$ and the stop cam $A\,T$. A motor drives this sleeve through a clutch, at a speed slightly higher than the speed of the transmitting shaft at the sending end. This increased speed is compensated for by delaying the brush arm after each character sufficiently to keep the sending and receiving stations in step.

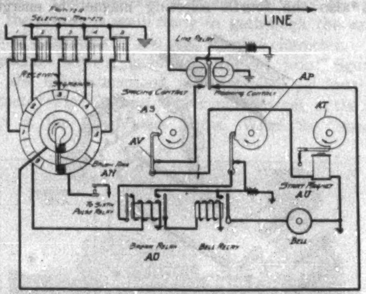

Fig. 6—Electrical Connections of Receiving Units

Normally the brush arm is held stationary by the start magnet $A\,U$ with the start magnet contact $A\,V$ closed. When transmission is started a spacing impulse precedes the bell and selecting impulses, a circuit is completed through the spacing contact of the line relay, the start magnet is operated, and the brush arm is released. After the brush arm is released it revolves at a rate of speed slightly higher than that of the transmitting brush arm but the distance from center to center of the receiving segments is such that the time required for the brushes to pass from the center of one segment to the center of the next is equal to the time required for the transmission of one impulse of unit length. The brushes therefore, pass over the center of the receiving segments during the middle of the incoming impulses.

Battery is connected to the solid ring of the receiving commutator whenever the line relay tongue moves over against its marking contact. Each one of the receiving segments is connected to a corresponding selecting magnet in the printer. If, therefore, the brush passes over receiving segment No. 1 while the line relay tongue is against its marking contact the first selecting magnet will be energized, and similarly with the second, third, fourth and fifth selecting magnets. As the brushes pass over each segment in turn they will or will not carry current to each successive selecting magnet according to whether or not the line impulse then being received is of marking or spacing polarity.

If a marking impulse is received directly after the start impulse the line relay tongue will be resting against its marking contact as the brushes pass over the bell segment B and the break relay $A\,O$ will be operated. This relay in turn operates a bell through the bell relay. Attached to the brush arm sleeve is a break cam $A\,P$ which breaks the locking circuit to the quick-acting break relay $A\,O$ just before the receiving brushes reach the segment B. If the receiving brushes reach this segment before the break key at the transmitting station is released, the break relay will again be operated before the slow acting bell relay has time to open the circuit to the bell. Only one bell signal is transmitted no matter how long the break key is held down.

After the brushes pass over the bell segment and the five selecting segments they complete a circuit through the marking contact of the line relay to the sixth pulse relay in the printer.

The printer, Fig. 7, used with this system, prints from a typewheel, which rotates to the proper letter and is then thrown forward against the paper. After each letter is printed the typewheel itself is stepped to the right, the paper remaining stationary, and at the end of each line of printing the paper is moved upward.

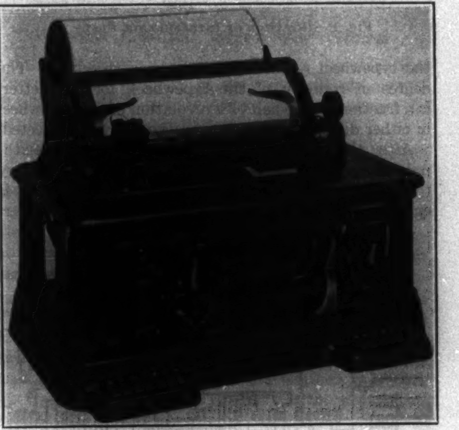

Fig. 7—Printer Used with Morkrum "Green Code" System

When a selecting magnet is energized, a disk or interference plate is rotated as shown in Fig. 8. There are four interference plates controlled by the first, second, third and fifth selecting magnets. The fourth selecting magnet does not move an interference plate but operates the fourth-pulse relay which in turn decides the direction of rotation of the typewheel.

The arrangement of the five-unit code (Fig. 1) is such that there are exactly 16 combinations which contain the fourth pulse and 16 combinations which do not contain the fourth pulse. The printer is arranged, therefore, so that whenever a code combination containing the fourth pulse is received, the typewheel revolves counter-clockwise and when a code combination that does not contain the fourth pulse is received the typewheel revolves in a clockwise direction. The degree of rotation of the typewheel, for any letter, is a fraction of one-half of a revolution of the typewheel in either direction depending on the character selected.

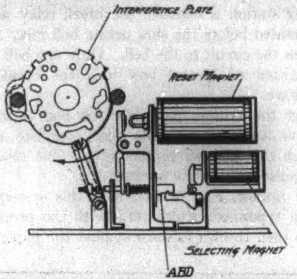
INTERFERENCE PLATE
RESET MAGNET
SELECTING MAGNET
ABD

FIG. 8—ROTATION OF INTERFERENCE PLATE

After the interference plates are moved, the sixth-pulse relay (Fig. 9) is operated and supplies battery to the drum magnet. When the drum magnet is energized it pushes a set of stop pins against the interference plates. These plates (Fig. 10) are cut out in such a way that only two pins are allowed to go through all four plates at any one time.

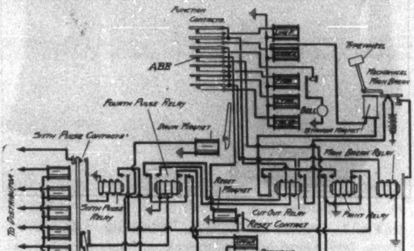
FUNCTION CONTACTS
ABB
TYPEWHEEL
MECHANICAL MAKE BREAK
FOURTH PULSE RELAY
DRUM MAGNET
BELL
STRIKER MAGNET
SIXTH PULSE CONTACTS
MAKE BREAK RELAY
RESET MAGNET
TO DISTRIBUTOR
SIXTH PULSE RELAY
CUT OUT RELAY
RESET CONTACT
PRINT RELAY
ROTATING MAGNETS
FOURTH PULSE CONTACTS
SELECTING MAGNETS

FIG. 9—DIAGRAM OF PRINTER CIRCUITS

If the letter "E" for instance is selected, the first interference plate is moved and the operation of the drum magnet pushes two pins through the interference plates. These pins *A Y* and *A Z*, are on opposite sides of an index arm *A W* which is connected to the typewheel by means of the square shaft *A X*. Inasmuch as the "E" code combination does not contain the fourth pulse, the fourth-pulse relay will not be operated and the operation of the sixth-pulse relay will connect battery to the *upper* set of rotating magnets thereby rotating the typewheel clockwise until the index arm *A W* strikes the pin *A Y*. If, however, the letter "D" is selected, not only the first selecting magnet but also the fourth selecting magnet is energized thereby operating not only the first interference plate but also the fourth-pulse relay. In this case the same pins are pushed through the interference plates as for the letter "E" but in the case of the letter "D" selection, the operation of the fourth-pulse relay directs battery to the *lower* set of rotating magnets, when the sixth-pulse relay is operated. The typewheel is then rotated counter-clockwise until the index arm strikes the pin *A Z*.

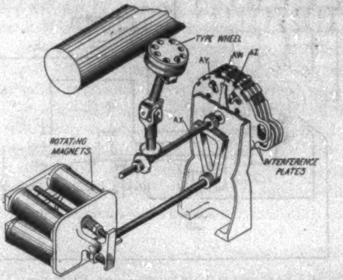
TYPE WHEEL
AY
AW
AZ
AX
ROTATING MAGNETS
INTERFERENCE PLATES

FIG. 10—OPERATION OF INTERFERENCE PLATES

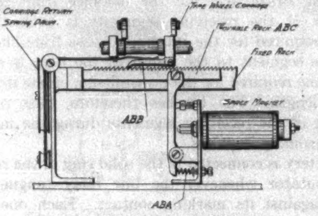
CARRIAGE RETURN SPRING DRUM.
TYPE WHEEL CARRIAGE
MOVABLE RACK ABC
FIXED RACK
SPACE MAGNET
ABB
ABA

FIG. 11—OPERATION OF SPACE MAGNET

When the pins are pushed through the plates a contact *A B E* (Fig. 9) is closed and the reset magnet (Fig. 8) is operated. The operation of the reset magnet restores the trip rods *A B D* and closes the reset contact (Fig. 9). When the reset contact is closed a circuit is completed through the print relay contacts and the striker and space magnets are energized. The operation of the space magnet (Fig. 11) compresses a spring *A B A* which in turn spaces the typewheel carriage forward when the space magnet is released. The striker magnet throws the typewheel against the platen thereby printing the selected character and opening the mechanical main break contact. The opening of the main break contact (Fig. 9) breaks the locking circuit to the sixth-pulse relay, and as the current to all of the magnets is routed through the sixth-pulse relay contact, battery is disconnected from the drum magnets, the rotating magnets, the striker magnet and the space magnet. The typewheel is spaced one space forward and the printer is again ready to gothrough the same cycle of operations for the next selected character.

Spacing between words, shifting to print figures, and the other functions, are controlled by function contacts (Fig. 9) located over notches cut in the top edges of the interference plates. When the "space" signal is received, for instance, the third interference plate is moved and a notch, under the space contact, allows the latter to close thereby connecting battery to the space magnet through one winding of the cut-out relay. When the space magnet is energized, the cut-out relay is also operated, closing a circuit to the main break relay. This relay opens the locking circuit of the sixth-pulse relay and disconnects battery from the space magnet. During this operation the reset magnet and the print relay are operated as usual but no printing occurs inasmuch as the circuit to the striker magnet is broken through the back contact of the cut-out relay.

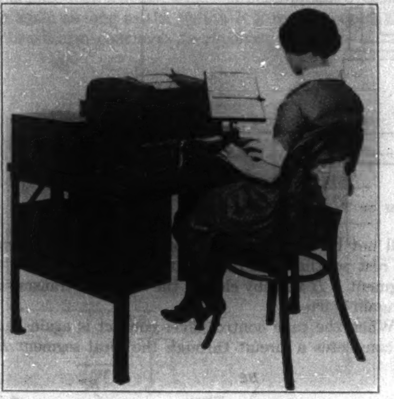

Fig. 12—Western Electric Terminal Set

On the under side of the typewheel carriage are mounted two pawls *A B B* (Fig. 11) which mesh with a fixed rack and a movable rack *A B C* located directly under them. When the spacing magnet is energized, the movable rack is moved to the left so that one of the pawls drops into the next tooth on the rack. When the spacing magnet is de-energized, the movable rack is returned to its normal position by the spacing spring *A B A* and moves the carriage forward one space.

When a "carriage return" selection is received, the carriage return function contact operates the cut-out relay and a carriage return solenoid. This solenoid raises a bar located between the two racks, lifting the pawls clear of the teeth. The typewheel carriage is then drawn to the left for a new line of printing by a cord wound around a spring-operated drum.

When the "figure shift" signal is received, the figures magnet is energized through the figures function contact and one of the windings of the cut-out relay. The figures magnet moves the typewheel upward, ready for the printing of numbers or punctuation marks.

When the "letter shift" signal is received the letters function contact is closed, thereby operating the letters magnet which releases the catch that holds the typewheel in its upper case position.

When the "line feed" signal is received, a line feed magnet is operated by the line feed function contact and, by means of a pawl and ratchet mechanism, feeds the paper upward ready for a new line of printing.

Western Electric "Start Stop" System

Fig. 12 shows a Western Electric terminal set. The perforator is shown at the right with the printer directly behind it and the transmitter is shown at the left in front of the distributor.

Transmission. Fig. 13 is a schematic wiring diagram of the circuits involved in transmitting signals over the line.

The Western Electric system is equipped for either direct keyboard or perforated tape operation and may be operated at any desired speed from 40 to 65 words per minute.

The tape that is prepared when the perforator is used is fed through the transmitter and is stepped forward once for every revolution of the transmitting brush arm *B B* in the distributor. Fig. 14 shows the tape feed mechanism. When the brushes pass over the transmitter segment *B C* (Fig. 13) the transmitter magnet (Fig. 14) moves lever *B D* about its pivot *B E* and feeds the tape forward.

When the transmitter magnet is de-energized, the tape pins *B F* move upward until the tops of the pins reach the level of the tape. If a pin is blocked by the tape the contact tongue *B G* remains against its spacing contact. If the perforations in the tape permit a pin to go through the tape, the corresponding contact tongue *B G* will move over against its marking contact. There are five pins *B F* and five contact tongues *B G* and each contact tongue is connected to a sending relay (Fig. 13). Consequently when the transmitter magnet is de-energized and battery is applied to the marking contacts, the proper sending relays will be energized according to the perforations in the tape. Whenever a sending relay is energized, it closes a

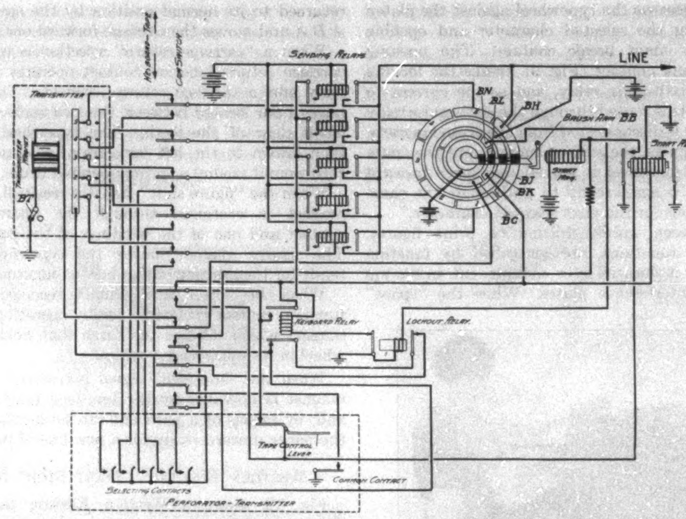
Keyboard-Tape
Cam Switch
Sending Relays
LINE
Transmitter
Transmitter Magnet
BT
BN
BL
BH
Brush Arm BB
Start Relay
Start Mag.
BJ
BK
BC
Keyboard Relay
Lockout Relay
Tape Control Lever
Common Contact
Selecting Contacts
Perforator-Transmitter

Fig. 13—Schematic Wiring Diagram of Transmitting Circuits

circuit to the corresponding transmitting segment and a locking circuit holds the relay operated.

To send a marking impulse, the line is closed, and to send a spacing impulse the line is opened. Segments *B H* and *B J* are wired so that when the brushes pass over segment *B H* the line will be closed and when they pass over segment *B J* the line will be opened. As the transmitting brushes revolve they first send out a spacing signal which is called the start impulse and then the selecting impulses in accordance with the code combination set up in the sending relays.

In order to send positive and negative impulses to the receiving station, a pole-changer may be operated from the transmitting segments. The signals are then sent over the line from the pole-changer.

For every revolution of the transmitting brushes, seven impulses are sent to the receiving station. Two are for synchronizing purposes and five are for selecting purposes but one of the synchronizing impulses is longer than the other. Communication is therefore carried on at a line frequency of between seven and eight units or between three and one-half and four cycles per character. Sixty words per minute represents a line frequency of a little over 21 cycles per second.

The transmitting brush arm *B B* is stopped once every revolution but is almost immediately released provided the tape control lever contact is closed. If, however, the tape control lever contact is open when the local brushes *B L* reach the segment *B K*, the circuit to the start relay will be open and the start magnet will not be operated. The brush arm will then come to rest so that the transmitting brushes rest on the segment *B H* thereby closing the line until transmission is again started.

When the tape control lever contact is again closed it completes a circuit through the local segment *B K* to the start relay and starts transmission. The start relay in turn operates the start magnet, the transmitting brush arm is released and circuits to the sending relays are closed through the marking contacts in the transmitter.

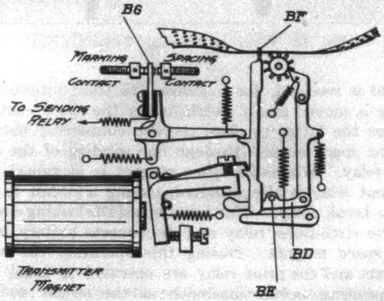
B6
BF
Marking Contact
Spacing Contact
To Sending Relay
Transmitter Magnet
BD
BE

Fig. 14—Tape-Feed Mechanism

When the local brushes leave the segment *B K*, the locking circuit to the start relay is broken, the start relay is de-energized and the circuit to the marking contacts in the transmitter is broken. During the time that the start relay is energized the selection is transferred from the transmitter to the sending relays ready to be sent to the receiving station one impulse after the other as the transmitting brushes pass over segments Nos. 1, 2, 3, 4 and 5.

Directly after the circuit to the marking contacts in the transmitter is broken the local brushes pass over segment *B C* operating the transmitter magnet and stepping the tape forward so that the next character in the perforated tape is presented above the pins.

If it is desired to repeat a character a number of times the switch *B T* may be operated to open the circuit to the transmitter magnet. Inasmuch as the tape is not stepped forward, the same character is sent over and over again as long as the switch *B T* remains open and the brush arm continues to revolve.

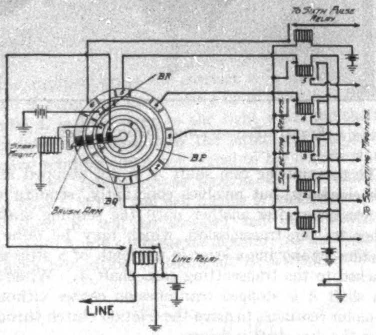

Fig. 15—Electrical Connections of Receiving Units

After the fifth selecting impulse is sent, the local brushes pass over segment *B N* and the lockout relay is energized. The operation of this relay breaks the locking circuit to the sending relays and the relays are de-energized.

As long as the tape control lever contact remains closed, the start relay and start magnet will be energized whenever the local brushes pass over the segment *B K* and the transmitting brush arm will therefore continue to revolve.

With direct keyboard operation the circuit to the transmitter magnet remains open and the selection that is set up on the selecting contacts in the perforator-transmitter, whenever a key lever is depressed, is transferred directly to the sending relays. From that point the operation of transmitting a character is practically the same as that described above.

In order to prevent sending a second selection to the sending relays before the first selection is sent over the line the common return wire from the keyboard selecting contacts is routed through the back contact of the keyboard relay which is in series with the locking circuit for the sending relays. When the sending relays are de-energized, by the operation of the lockout relay, the back contact of the keyboard relay is again closed permitting the next selection to be sent from the selecting contacts to the sending relays.

With keyboard operation a contact that is closed by the operation of the keyboard relay takes the place of the tape control lever contact described above. The transmitting brush arm stops, therefore, after every revolution and remains stationary until a key lever is depressed and the keyboard relay is operated.

Reception. Fig. 15 shows the manner in which the receiving units are connected electrically.

The light brush arm is clutch-driven and the speed of the shaft that drives the brush arm is the same as the speed of the transmitting brush arm at the sending end. When the start impulse is received the receiving brush arm is released and revolves at the same speed as the transmitting brush arm.

Normally the brush arm is held stationary by the start magnet with the local brushes resting on the start segment *B Q*. When the receiving brushes are at rest and the line is opened battery is supplied to the start magnet through the back contact of the line relay and the brush arm is released.

When the line is closed battery is connected to the segment *B P* through contacts on the line relay, and when the line is opened battery is cut off. If the line is closed, therefore, when the receiving brushes pass over segment No. 1, the first selecting relay will be energized and similarly the second, third, fourth and fifth selecting relays. As the brushes pass over each segment in turn they will or will not carry current to each successive selecting relay according to whether the line is closed or open at that particular instant.

After the brushes pass over the five selecting segments a local circuit is completed through segment *B R* and segment No. 6 to the sixth-pulse relay in the printer and the brush arm is again stopped by the start magnet armature.

The printer, Fig. 16, is of the movable-carriage type where the paper that receives the message is moved one space to the left after each character is printed. Printing is accomplished by pushing the paper against a type wheel which revolves in one direction on a vertical shaft and which may be raised or lowered for printing upper or lower case characters. This printer is described in J. H. Bell's Institute paper on printing telegraph systems and therefore needs no further mention.

Kleinschmidt System

Fig. 17 shows a Kleinschmidt terminal set. The perforator is shown at the right and the printer at the left with the transmitting and receiving distributors between them.

Transmission. Fig. 18 is a wiring diagram of the circuits involved in transmitting signals over the line. The transmitting mechanism is entirely mechanical and is like that of a Wheatstone transmitter.

The tape that is prepared by the perforator is fed through the transmitting distributor and is stepped forward by means of the cam *H* and the pawl *J*, once for every half revolution of the transmitting shaft *A* (Fig. 19). For every revolution of the transmitting shaft two characters are sent over the line.

The transmitting cam shaft *A* is motor-driven through a friction clutch at any desired speed from 40 to 80 words per minute. As the shaft *A* revolves, the cam *B* moves lever *C* about a pivot *D* allowing the spring *E* to draw the pin *F* upward. If a hole in the perforated tape presents itself above the pin *F*, the latter pin will pass through the tape and the contact tongue *G* will move over against its negative or marking contact as shown. If, however, the pin *F* is blocked by the tape, the contact tongue *G* will remain against its positive or spacing contact as illustrated in Fig. 20. Six cams *B*, six levers *C* and five pins *F* are located one behind the other and operate in succession.

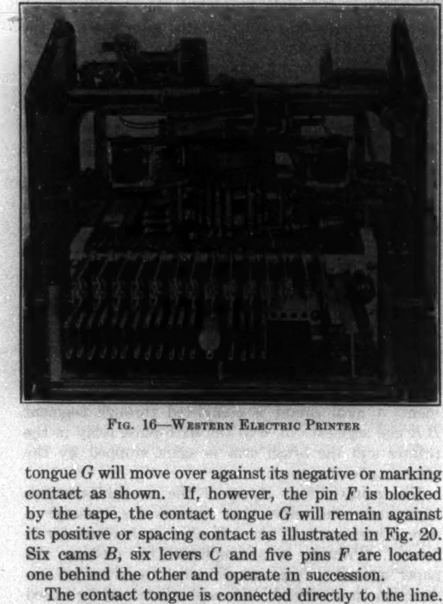

FIG. 16—WESTERN ELECTRIC PRINTER

The contact tongue is connected directly to the line. Positive and negative impulses are therefore sent over the line as the five pins *F* move upward, one after the other, and are blocked or are not blocked in accordance with the perforations in the tape.

At the beginning of every character one of the cams on the transmitting shaft *A* actuates a train of mechanism similar in every respect to that described above, except that no vertical pin *F* is included. At the beginning of each character the transmitting tongue moves to the right and sends out a marking impulse. This impulse is followed by the five selecting impulses and then a spacing impulse.

For every character transmitted, therefore, seven impulses are sent to the receiving station. Two are for synchronizing purposes and five are for selecting purposes. Communication is carried on at a line frequency of seven units or three and one-half cycles per character. Sixty words per minute represents a line frequency of 21 cycles per second.

FIG. 17—KLEINSCHMIDT TERMINAL SET

The transmitting cam shaft *A* is not stopped after each character, but revolves constantly, sending out one character after another until the sending station wishes to stop transmission, which may be done at any time by moving a lever in the path of a stop arm attached to the transmitting cam shaft *A*. When the cam shaft *A* is stopped transmission ceases although the motor continues to drive the friction clutch through which the cam shaft is driven.

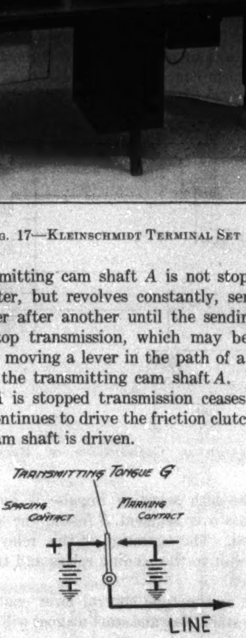

FIG. 18—DIAGRAM OF MARKING AND SPACING CONTRACTS

If, for any reason, it is desired to repeat a character a number of times, the button *O* (Fig. 20) may be depressed so as to hold the pawl *J* out of engagement with the tape feed wheel ratchet. In this way the tape will remain stationary and the same character will be sent over and over again as long as the transmitting cam shaft *A* continues to revolve and the button is depressed.

In order to signal quickly to the distant station, a bell signal mechanism is provided as illustrated in

Fig. 21. Shaft *K* is clutch-driven and revolves only when the bell handle *L* is moved to the right. When the handle *L* is moved to the right, and then released, the shaft *K* is released and the transmitting cam shaft *A* is stopped during one revolution of the shaft *K*. During this revolution the cam *M* moves the contact tongue *G* back and forth by means of the levers shown, sending the characters "figure shift," "J," and "letter shift" over the line. Whenever the letter "J" is selected in the printer, while the carriage is in the upper case, a bell is rung and no printing takes place. If the bell handle *L* is held over to the right when the shaft *K* completes one revolution the latter will continue to revolve sending out a bell signal to the distant station once every revolution as long as the bell handle is held over. When the bell handle is released, however, the shaft *K* will be stopped and the transmitting cam shaft *A* will continue its motion. At the beginning of each revolution of the shaft *K*, a small mechanical bell is operated so that the operator at the sending station may know how long to hold the bell handle *L* to the right in order to send out any desired number of bell signals.

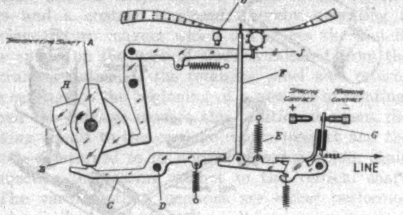
O
Transmitting Shaft A
J
F
H
Spacing Contact
Marking Contact
+
−
E
G
B
LINE
C
D

Fig. 19—Tape-Feeding Mechanism—Marking Contact

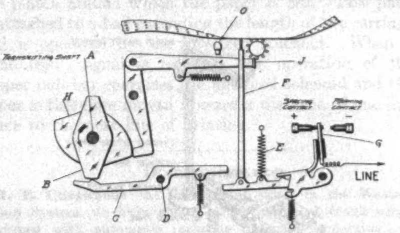
O
Transmitting Shaft A
J
F
H
Spacing Contact
Marking Contact
+
−
E
G
B
LINE
C
D

Fig. 20—Tape-Feeding Mechanism—Spacing Contact

Reception. Fig. 22 shows the manner in which the receiving units are connected electrically.

The receiving distributor is entirely separate from the transmitting distributor. This necessitates two motors, but with this arrangement transmission may be carried on in opposite directions at different speeds and accurate speed adjustments are not necessary. The light brush arm *N* is clutch-driven at a speed slightly faster than the speed of the transmitting cam shaft at the sending end. This increased speed at the receiving station is compensated for by delaying the brush arm, after each character is received, sufficiently to keep the sending and receiving stations in step.

Normally the brush arm is held stationary by the start magnet armature with the brush resting on the start segment and the relay tongue held against its spacing contact. When a character is received a marking impulse precedes the first five selecting impulses and a circuit is completed through the marking contact of the line relay, the start magnet then is operated and the brush arm released.

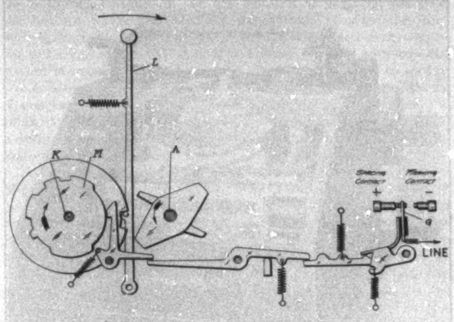
L
K
M
A
Spacing Contact
Marking Contact
+
−
G
LINE

Fig. 21—Bell Signal Mechanism

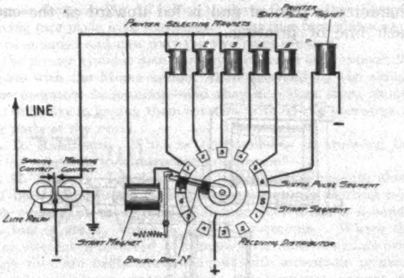
Printer Selecting Magnets
Printer Sixth Pulse Magnet
1
2
3
4
5
LINE
Spacing Contact
Marking Contact
Line Relay
Start Magnet
Brush Arm N
Sixth Pulse Segment
Start Segment
Receiving Distributor
−
+

Fig. 22—Electrical Connections of Receiving Units

Positive battery is connected to the solid ring of the receiving distributor and the marking contact of the line relay is in series with the common return wire for the selecting magnets and the start magnet. Each one of the selecting magnets in the printer is connected to a corresponding receiving segment. If, therefore, the brush passes over receiving segment No. 1 while the line relay tongue is against its marking contact, the first selecting magnet will be energized and similarly the second, third, fourth and fifth selecting magnets. As the brushes pass over each segment in turn they will or will not carry current to each successive selecting magnet according to whether or not the line impulse then being received is of marking or spacing polarity.

After the brushes pass over the five selecting segments they pass over a sixth-pulse segment, completing a circuit through the sixth-pulse magnet in the printer and then again come to rest on a start segment.

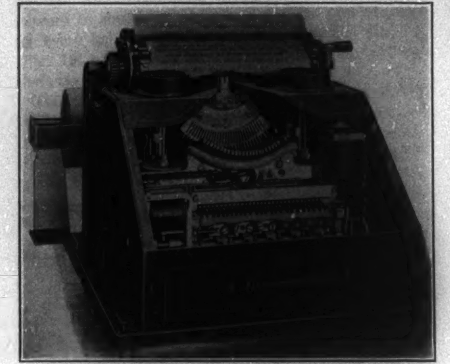

Fig. 23—Kleinschmidt Printer

The printer, Fig. 23, is a type-bar printer of the movable-paper carriage type similar to a standard typewriter. The paper is moved to the left after each character is printed and is fed upward at the end of each line of printing.

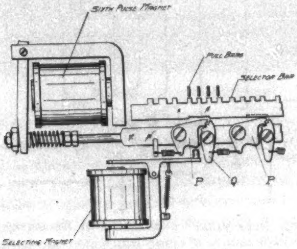

Fig. 24—Operation of Selecting Magnet

When a selecting magnet is energized its armature lifts a pawl *P* (Fig. 24) in the path of a selector bar and a latch *Q* locks it in this position. Five pawls *P* are located on a bar that is moved by the sixth-pulse magnet. When the selection is stored up in the pawls on this bar, the sixth-pulse magnet is operated and the pawls that were lifted move the corresponding selector bars to the right.

Each type-bar (Fig. 25) is connected to a pull-bar mounted directly above and at right angles to the selector bars. When one or more of the selector bars is moved to the right a slot is presented under one of these pull-bars and the selected pull-bar drops so that a hook on the under side of the pull-bar is in the path of an operating bail *R*. This bail is moved by an operating solenoid whenever a pull-bar drops into a slot in the selector bars. In this way the selected type-bar is thrown upward and the proper character is printed.

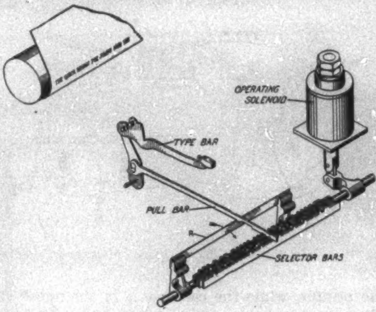

Fig. 25—Operation of Type Bar

Spacing after every letter is provided for by means of a spacing solenoid which is energized whenever a type-bar moves upward. Spacing between words is accomplished in a similar manner except that the type-bar selected does not carry any type and therefore does not print.

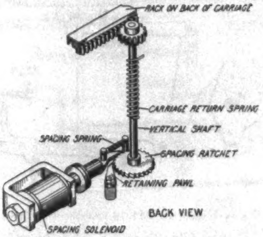

Fig. 26—Operation of Carriage

On the back of the carriage a rack (Fig. 26) is mounted which meshes with a gear on top of a vertical shaft. The spacing solenoid turns the ratchet on the bottom of this vertical shaft, the motion being transmitted to the carriage by means of the vertical shaft, and the carriage is thus stepped forward after each character is printed. The spacing ratchet is not rigidly attached to the vertical shaft, however, but drives it through a clutch (not shown). A carriage return spring is wound up as the carriage is spaced along and exerts a force on the vertical shaft tending always to return the carriage to the beginning of a new line of printing. When the clutch is in its normal closed position this force is held in check by a retaining pawl acting against the spacing ratchet. When the "carriage return" signal is received, the "carriage return" pull-bar drops into its notch in the selector bars and a contact is closed, thereby operating a carriage return magnet which disengages the clutch. The spring on the vertical shaft is released from the restraining action of the retaining pawl and returns the carriage to the beginning of a new line of printing. When the carriage reaches this position it opens the locking circuit to the carriage return magnet and the clutch is returned to its normal closed position, again connecting the spacing ratchet to the vertical shaft.

The various other functions are either performed mechanically directly from the pull-bars or are operated by means of solenoids controlled by the pull-bars.

When the "figure shift" signal is received, for instance, the "figure shift" pull-bar drops into its notch in the selector bars and a contact is closed thereby energizing the shift solenoid. The latter then lifts the front end of the carriage and a latch holds it in its shifted position so that figures or punctuation marks may be recorded. When a "letter shift" signal is received and the "letter shift" pull-bar is moved forward by the operating bail the latch is released mechanically and the carriage drops back to its normal position.

A ratchet that is operated by a pawl is mounted on the platen around which the paper is fed. This pawl is attached to a bail extending the length of the carriage and is operated by the line feed solenoid. When a "line feed" signal is received, the operation of the proper pull-bar energizes the line feed solenoid and the paper is therefore moved upward a distance of one line space to the next line of printing.

Discussion

R. E. Chetwood: At the present time, in the Western Union System, we have about 185,000 miles of trunk wires, equipped with automatic, printing telegraph apparatus. If the automatic apparatus had not been used it would have required approximately 460,000 miles of wire to handle the same amount of traffic. That shows a great saving in wire plant, due to the use of automatic apparatus.

Another figure that possibly would be of interest is that today approximately 75 per cent of the trunk line traffic is handled by automatic apparatus. By automatic apparatus, I refer to apparatus of the type described in the paper and also the heavy traffic apparatus which was described in Mr. Bell's paper of two years ago.

John H. Bell: The author has not mentioned that all three systems can be operated duplex. As a result of this omission the following sentence in the first column of page 89, towards the bottom which reads: "This necessitates two motors, but with this arrangement, transmission may be carried on in opposite directions at different speeds and accurate speed adjustments are not necessary," might lead one to think that in order to secure transmission in both directions, that is, to operate duplex, it is necessary to have two motors. Such is not the case. I think it was Mr. Reiber's intention to emphasize the fact that a different speed in each direction is obtained by the use of two motors.

He might have claimed for printing telegraphs the advantage of greater accuracy. In the majority of the operating rooms of one of the largest telegraph companies in this country, there are large notices reading: "Accuracy First." In the final analysis, the standard of accuracy depends upon the operator, but the use of printing telegraphs enables the operator to give so much more time to the checking of the messages that the standard of accuracy is considerably higher than with the old Morse instruments. As a matter of fact, I believe that the number of undetected errors in the case of printing telegraph systems is only about thirty to forty per cent of the number of undetected errors with Morse.

Just picture a telegraph organization in a position to print at the bottom of each message blank which goes out to the public—"There is no error in this message". The use of the printing telegraphs has made it possible to proceed a long way toward that high standard.

While on the subject of accuracy, I will mention one or two slight inaccuracies in the paper. Fig. 16 shows the Western Electric printer with relay box as arranged for multiplex operation, which is different from the arrangement for the start stop system as shown in Fig. 12. Fig. 15 shows the Western Electric receiving face plate with four rings. Four ring face plates have been abandoned and now only the two rings are used.

If the printer systems described by Mr. Reiber can successfully compete with the Morse system when operated by the skilled Morse operators in America—and they do—then there should be no difficulty in having them compete with Morse operators in other parts of the world.

G. D. Robinson: What is the possibility of applying the printing telegraph to wireless communication?

A. H. Reiber: I believe there will be developments along those lines in the future. In applying automatic printing telegraph equipment to wireless communication there is a condition, that of static, which is hard to overcome. Where the human element is involved, it is possible to receive signals even though they are badly mutilated but with automatic printing telegraph equipment, unless future developments correct the difficulty, static disturbances will occasionally cause unintelligible words.

On Deviations From Standard Practise in Lightning Arresters

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Associate, A. I. E. E.
General Electric Company, Schenectady, N. Y.

***Review of the Subject.**—This paper is an endeavor to answer questions of practise and criticism of arresters brought out by an investigation conducted by the Protective Devices Committee.*

For the most part practise in lightning arresters is standardized. In fundamental principles there have been no changes for many years. Improvements in details, especially of construction, are still being made. A new arrester, the oxide film arrester, gets rid of the oil and electrolyte and avoids the necessity of daily charging, but fundamentally it is designed along the same principles as the aluminum arrester. The important principle is the electric valve action—there are but a few milliamperes of discharge rate at normal line voltage, but at abnormal line voltages the discharge current rise to hundreds of amperes. In answer to criticisms made by a few prominent engineers, it is maintained as fundamental that a large discharge rate for an arrester is an absolute essential. The burden of proof falls on those engineers who use arresters of low discharge rate. These arresters cannot discharge the dangerous lightning surges on overhead lines. Since there are lightning arresters of low discharge rate in apparently satisfactory use, an explanation for this anomaly is found in the use of insulators of low arc-over voltage. Either the lightning potential is relieved locally at the insulator or the resultant traveling wave is of too low voltage when it reaches the transformer greatly to endanger the insulation. Poor line insulation is not a solution of the problem of continuity of service. Why not save the cost of the useless lightning arrester?

The current in such a traveling wave is about two amperes for every thousand volts of lightning potential, 600 amperes for 300 kv. One to twenty-five ampere discharge rate of arresters has little effect in reducing the lightning voltage.

How many arresters should be used to protect a six-feeder system? It depends on the conditions of insulation in circuit breakers and the importance of continuity of service. According to the conditions discussed in the body of the paper, from one arrester connected to the busbars to seven arresters with auxiliaries are needed.

The use of no arresters is discussed from three standpoints.

1. If it is contended that lightning is not of sufficient voltage to cause damage. 2. If it is considered a better investment to put lightning arrester money into spare transformers. 3. If it is considered good practise to so highly insulate a transformer as to give it immunity from lightning. The conclusion reached is that each of these three arguments is dangerously faulty.

A new method of inspection of aluminum arresters is proposed. The experiments given in the paper show that the power factor of the cells examined is very sensitive to their condition. There are promises of effecting economies in overhauling aluminum arresters and of lengthening their life. Experiences are given with a 33-kv. arrester in service thirteen years without overhauling. The plates are still in good condition. The usual damaging deposits of decomposed oil on the aluminum film were prevented by using an initial rush of charging current great enough to throw them off. The electrolyte is partially exhausted in strength and needs changing. The discharge rate is still high.

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COMMITTEE SURVEY. For several successive years the Technical Committee on Protective Devices, Mr. D.W. Roper, Chairman, has voted to make a survey of practise in lightning arresters on transmission circuits (not distribution), but each year there have been other matters which took precedence.

Last year Mr. F. L. Hunt addressed a number of eminent transmission men with definite questions relating to specific cases designed to bring out views on advisable practise and to obtain adverse criticism. In general their answers represent standard practise. There are a few variations from, what seems to the writer, good practise. These variations will be discussed briefly by a presentation of definite reasons against them.

Object. Briefly the object of this paper then is to discuss: First, variations from good practise, and second, proper differences in standard practise, which will be treated under one heading; and third, improvements and economies in the maintenance of aluminum arresters.

DIFFERENCES IN STANDARD PRACTISE

Status of Lightning Arrester Practise. Established practise in lightning arresters is firmly based on sound scientific principles. There is still a number of unknown conditions and even the best developed devices fall short in certain ideal functions, but engineering judgment is found in every step.

Horn-Gap Arresters and Any Other Type of High Series Resistance. The initial discussion will be on the extremes of differences from standard practise, such, for example, as the use of horn-gap arresters and the practise of using no arresters at all. A brief review of some of the factors relating to arresters not of the electric valve type follows: (1) Horn gap with high series resistance, (2) with medium resistance, (3) with no series resistance.

(1) If a horn-gap arrester has a discharge rate of the order of 10 *amperes* it is *insufficient to relieve the potential of any dangerous induced lightning stroke.*

(2) If the discharge rate is of the order of 100 amperes the arrester becomes more protective in proportion but the amount of power taken by the arrester from the circuit makes both a heavy draft on the

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generators and a difficulty in the design of the arrester. If it is designed with generous proportions to avoid overheating of series resistance the cost will be high.

Commenting on these factors: The power taken by a three-phase discharge of horn gaps with currents limited to 100 amperes on a 60-kv. circuit is about 12,000 kw. The usual time required for the arc to rise on a horn is about 5 seconds. No such discharge rate is used on these arresters in general because the resistance would be overheated by the power current which follows the lightning discharge. This energy would heat 600 liters (150 gallons) of electrolyte through 100 deg. cent. In so doing the resistance would reduce to a fraction of its initial value, due to the negative coefficient of resistance with the rise of temperature—a natural characteristic of electrolytes.

Commenting further on that persistent and inefficient device, the arrester of any type of low discharge rate, proof is herewith offered, in the following paragraph, that such an arrester has no value in discharging lightning.

Current of Traveling Wave: A traveling wave has an average current of two amperes per thousand volts of potential of the wave. For the argument following it is necessary to accept this numerical figure.

Proof that the approximate current in a traveling wave is two amperes per kilovolt of surge voltage follows.

The energy in a traveling wave is half electromagnetic and half electrostatic (see any standard work on this subject, for example such authorities as Bedell and Crehore, Steinmetz, Pupin, Berg).

Expressed in a formula

$1/2\, C V^2 = 1/2\, L I^2$ where the capacitance C and the inductance L of a single wire are taken for any chosen unit of length of the wave. V is the effective voltage and I is the effective current over the length of wire chosen as a unit. Or V and I may be used as the crest voltage and crest current. By simple transposition and cancellation the value of surge current I in terms of the surge voltage becomes

$I = V \sqrt{C/L}$ = approximately 2 amperes for No. 0, B & S. wire at an average height of 30 ft. (900 cm.) above the conducting surface of the earth.

The inductance L of a single wire with the surface charge on the earth is not a definite quantity, but its widest possible variation will not affect the final results greatly because this factor appears under a square root sign. The value of inductance L used was calculated on the basis that the electromagnetic field of a line wire extended to its image at a depth below the surface equal to the height of the wire above. The single wire inductance was then used. The actual inductance is more likely to be greater than less.

To illustrate how much effect the size of wire and its height may have on the surge current there were chosen two extreme cases. First, a large wire, one million circular mils, at an average height of 25 ft. (750 cm.) was used, and this increased the surge current of a single wire by only 18 per cent. Second, a small wire, No. 6 B & S, at a considerable average height, for the lowest wire 40 ft. was chosen. This lowered the surge current of a single wire to only about 90 per cent of that in the No. 0 wire at 30 ft. (900 cm.) height.

Significance of the Current in a traveling wave. If, then, a traveling wave on a transmission wire has an average current of 2 amperes per thousand volts (about 10 per cent more or less according to the dimensions, spacing, and height of wires), a lightning charge of 200,000 volts would have a current of 400 amperes in its traveling wave. This wave travels at 300,000 kilometers per second (184,000 miles a second), and an arrester which can draw off only 10 amperes from the 400 amperes, as this traveling wave rushes headlong into the insulation of the transformer, is not doing much to reduce the voltage of that wave. If by assumption the traveling wave has only 10 amperes of current its voltage is only about 5 kv. and is harmless to any transmission circuit.

The lightning arrester can take only a share of the current as the traveling wave reaches the point where the arrester is located. In other words, if the arrester is at any point on the line except at the ends the lightning current will divide into two parts—one part continuing along the line and the other part passing through the arrester to ground. The voltage of the traveling wave is not reduced even in proportion to the reduction of the current involved in the wave. This is because half the energy of the traveling wave is electrostatic and half electromagnetic.

In this argument is there anything subtle or vague or improbable? It requires only the acceptance of the figure of two amperes per kilovolt in the traveling wave and the well-known theory of the division of current at a bifurcation of the circuit. This same argument applies to any lightning arrester of any make which has a low rate of discharge. It puts the burden of proof for such American and European practise as high resistance and a jet of water used as a lightning arrester, on the engineers who advocate it.

Furthermore, all our laboratory experience shows that such a jet of water or any lightning arrester of low discharge rate has no appreciable value in discharging a traveling wave.

(3) If no series resistance is used the large arcs of short circuits which can be blown for 30 or 40 feet to other circuits call for large space of installation. Also there is the inevitable interruption of service to say nothing of other intrinsic dangers of short circuits. Still further, if separate grounds for the three phases are used for these horn gaps, the space between grounds becomes a menace to life. The arrester does not sustain the line voltage but throws it down to the ground. This menace increases with the potential and power of the circuit. As another objectionable feature, the earth contacts dry out under heavy discharge. The earth resistance may amount to any high value. There

are other objections to these short circuiting devices from a protective standpoint.

In going over these matters with an interested transmission engineer, he asked at this point the very pertinent question: How is it that a prominent engineer, whose judgment and veracity we both respect and who has no personal interest in the manufacture or sale of lightning arresters of the horn gap type, could install horn-gap arresters of comparatively low discharge rate on his circuits and honestly report successful operation?

In answer, there might be several ways that this condition could come about. As an illustration, if the insulators on a transmission line have an arc-over voltage of the order of say 120 kv. and the power voltage is 60 kv., lightning could not induce on the line more than double the normal line voltage without spilling over an insulator and relieving itself locally at the point on the line nearest the stroke between cloud and ground. The traveling wave is only about 70 per cent of the arc-over voltage of the line insulator, due to the lightning charge breaking into two parts which travel in opposite directions from the place of maximum induction (Fig. 1).

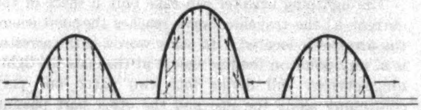

FIG. 1

Traveling wave to the left, one-half of the initial energy.

Initial charge which is momentarily stationary.

Traveling wave to the right, one-half of the initial energy.

The insulation of the transformers is designed to withstand a test of double voltage for a minute. The only danger of this traveling wave lies either in a steep wave front which would damage the insulation between end turns, or in some remote possibility of an internal resonance in the transformer coils. The chances of damage are very slight. Then arises the question when such a condition of line insulation exists—why even go to the expense of the useless horn-gap arrester? An engineer may have inherited these conditions of low insulation on the line and may be making the very best engineering practise out of a bad situation, keeping very properly in mind the dividends to the stockholders. We venture to say, however, that this same engineer would not recommend low dielectric strength of insulators or a revival of the once tried practise of placing horn gaps at every insulator. The best practise today is in the direction of the highest reasonable factor of safety in the spark potential of the insulators.

Another way in which the user of a horn gap arrester of low discharge rate could escape without loss of insulation of the transformer is by using a horn gap without resistance, in parallel with the resistance type. In this case the dielectric strength of the insulators may be very high and the voltage of the traveling wave may be at a damagingly high value, and yet damage to the insulation of the transformer may not be evidenced. However, it is not a solution of the problem, because the primary object of a transmission system is to sell and deliver power. The power service is interrupted by the short circuit of the horn gap.

The Effect on Practise of the Demands of Continuity of Service. The foregoing statement of service brings us immediately to a difference in arrester practise between engineers of different systems in which they can all be right. At one extreme there is the demand of service so slightly emphasized as to make it permissible to disconnect the power from the line during lightning storms. If visual observation and storm detectors could be relied on there would be little need of lightning arresters under a condition of this kind. Any one might take a chance without being criticised.

At the other extreme is the requirement of service illustrated by the Edison companies where one interruption in ten years is considered a calamity. In between are all grades of requirements brought about by the supply of power to such industries as paper mills, mining pumps, weaving mills, and manufacturers of any material which requires a continuous movement of the machines from the beginning to the end of the piece being manufactured.

There is another factor relative to the installation of an arrester of low discharge rate which has not been sufficiently emphasized, namely that no matter what type of arrester is installed the expense of installation is always considerable. If the expense of the installation is to be undertaken, why not add a little more and get an effective discharge rate?

A large concern whose business is enhanced by perfect service of its main apparatus in the form of generators, transformers, motors, lamps, etc. cannot argue the case for a cheap ineffective lightning arrester and build up a business in this line based on incomplete and immaturely considered experiences.

The foregoing argument does not take into account the sincerity of research engineers who have collected and analyzed voluminous data for many years and have concluded that it is an economic waste to the art of transmission to invest in arresters of low discharge rate as now installed. To any one company the futile expense may not be damaging but the aggregate loss for the country over is very considerable. The idea of giving a new arrester a trial indicates an admirable progressive spirit. But to do this without considering the intrinsic factors or the characteristics of the arresters entails unnecessary waste. It is one of the objects of this discussion to present reasons for present practise and thereby give the dissenter an opportunity to present his side in open forum. The dissenter also owes it to the art to set us right, if we are wrong, and thereby effect a still greater saving in investment.

The Practise of Using No Lightning Arresters. We now pass on to another extreme of practise, namely, the system which operates without any lightning arrester. There is only one such overhead system of importance that I know of. What penalty it is paying for this practise is not yet fully determined. What financial losses are entailed? What kind of service is given? A review of the evolution of this condition may be valuable in preventing some other system from attempting the same practise without having the same conditions. The transformers on this system were rewound with extra-high insulation at a very considerable expense. This is the first and most important item. Aluminum lightning arresters were used in the earlier days, the neutral was non-grounded, and the practise of keeping the power on the circuit regardless of the conditions did, in one case I know of, hold a persistent arcing ground for ten hours. Naturally an aluminum lightning arrester was destroyed and the remarkable feature was it lasted the ten hours. At that time the engineer argued that he was willing to sacrifice the arrester to maintain the service, but he lost both the arrester and the service. Under this practise one arrester after another disappeared and there is no desire on the part of a manufacturer to sell more arresters. There are certain lines of argument that one may follow regarding this installation. (1) It may be contended that the lightning is not of sufficient voltage to cause any damage; or (2) it may be considered a better investment to put the lightning arrester money into spare transformers; or (3) it may be considered good practise to so highly insulate a transformer as to give it a high degree of immunity from lightning.

Considering these three possible arguments in the order given above, first, that the lightning may not be of sufficient voltage to damage the insulation—if the lines are highly insulated—one can only say, Alas! Tests made in the laboratory on coils representing end turns of a transformer have demonstrated the ease with which a spark may be formed between adjacent turns puncturing the insulation. To note this tendency on transmission lines the simplest method is to place a spark gap in parallel with a choke coil of comparatively few turns. During lightning storms frequent sparks will take place. Another situation where this effect is shown is the frequency of puncture of current transformers by traveling waves. Many such experiences have led to the conclusion that traveling waves, especially of steep wave front, will cause punctures between turns of the end coils of transformers—certainly they do in extreme cases of high voltage. This would require the best protection obtainable. To be sure, a single puncture of this kind does not, in general, cause short circuit, but the successive sparks may be cumulative in their effects, punctures being made at different points until the conditions are right for holding the arc. Small transformers and very large ones are more likely to fail than intermediate sizes due to the distribution between layers or between turns. More technical data on this subject are needed and are being collected.

Second, the spare transformer method of caring for dangerous lightning strokes needs comment. It is not necessarily a poor engineering proposition. On the contrary there are conditions which make it acceptable. As an example of an installation of a step-down transformer, if the requirements of continuity of service are rigid, if the transformers are of low kilowatt capacity and of high voltage, it is difficult to figure economy in an investment in a lightning arrester. Arresters have a way of mounting in cost as the required voltage of the circuit is higher, regardless of the kilowatt capacity of the transformer. We have given this matter attention for several years without being able to evolve a satisfactory arrester. Such an arrester must have the characteristics of low cost, high discharge rate, independence of attention, and practical indestructibility.

Admitting then there is now no acceptable standard practise for application of lightning arresters for high-voltage transformers of low kilowatt capacity, let us turn attention to those of higher capacity such as are installed in power stations and principal step-down stations. Will the service demands permit an interruption while a spare transformer is shifted from one station to another? Shall a spare transformer be ordered for each station? Shall it be single- or three-phase? If a lightning storm should damage two single-phase transformers out of the four available, would the loss of revenue, to say nothing of the prestige, far exceed the interest and depreciation on one set of arresters at this point—or even several sets of arresters included in a proportional charge? Is it worth the price to risk a possible cumulative damage to the insulation of generators and transformers by occasional heavy discharges without arrester protection? Where the answer is yes, the case is settled. Every transmission engineer must find a balance between the risk of no protection and the cost of failure without protection. The primary question for self-interrogation in any particular installation is: What will it cost in loss of revenue, in time, in repairs, and in prestige to have a failure of one, two or of all three phases? Lightning storms average up if the effects of enough of them are taken into account. The chances of a stroke near a station are not very great. In lightning-infected countries one must in general by pure chance expect, some time, a progressive thunder storm which, instead of crossing the lines at an angle, runs longitudinally with it, with practically every stroke effective in producing a high-voltage surge on the lines or in the station. One can go several years with hearty self-congratulation instead of lightning protection and finally meet a longitudinally traveling Waterloo.

It has been and still can be properly argued that many or even the majority of discharges of lightning arresters are unnecessary as the charges are harmless. This is true where the gaps of the arresters are set at a spark voltage only slightly above line voltage. But such an argument does not decrease the intensity of the minority of discharges, nor does it prove that arresters are not necessary for protection for the lesser number of heavy strokes or that it is good judgment to do without arresters entirely.

To summarize some of the points: Arresters may be dispensed with (a) if there are no lightning storms and no surges on the lines; (b) if the insulation of the power apparatus has a higher factor of safety than the line insulators (leaving a chance of damage by a stroke near the station); (c) if there is available a good detector of lightning as it approaches the lines and the circuit breakers are opened before the storm breaks anywhere over the aerial line; (d) if the transformers are of such low kilowatt capacity that the relative cost of the arrester is above the economical dictates of risk and replacement of damaged transformer Loss of service to the customer and the interruption of the main power service by accidental failure of a small power transformer must at present be carried on the debit side of the book value of this customer's payments. At present the lack of acceptable solution of this problem is interfering with the installation of small-power transformers on high-voltage circuits. This is a condition the manufacturer of transformers regrets as much as the power company and is as eager to correct; (e) on underground systems with grounded neutral, arresters may be used sparingly.

Third. As to using thicker insulation instead of lightning arresters—thicker insulation on the transformer turns of the coils engenders more difficulties in extracting the heat from I^2R losses and lessens the kilowatt capacity of the transformer. Since it seems impossible to put on enough insulation to prevent all lightning troubles it has become standard practise to use a reasonable amount of insulation and employ a lightning arrester. The arrester seems necessary anyhow for occasional extreme voltages.

Taking up one of Mr. Hunt's questions relative to the installation of lightning arresters on a circuit consisting of six feeders leading out from a bus—he has received the answers that, at one extreme of practise a lightning arrester should be placed on each one of the six outgoing feeders; at the other extreme, either one lightning arrester on the bus is recommended or none at all if the feeders are cables. If the feeders are important, the lightning frequent, the service demands rigid, the six arresters are desirable. Even greater protection may be necessary. If, on the other hand, the demands of protection are not great, then one or two arresters on the busbars would be sufficient. Two arresters are recommended when it is important to have one as a spare. One arrester of high discharge rate reduces the risk to a small value. However, if this practise of using one arrester is followed there are two important things that must be done at the same time: First, the current transformers must be shunted by bypass gaps; second, since the arrester is on the generator side of the automatic circuit breakers the circuit should be protected against accidental short circuit by suitable fuses on the arrester.

Engineering judgment must be used and all the factors of protection taken into account in order to decide how many lightning arresters to install on these six feeders and how to place them. I shall now take another hypothetical case, not unknown in practise, in which even the installation of six arresters does not give good protection. Suppose the line insulators have an unusually high factor of safety against lightning potential. This is good practise. Money could scarcely be better invested in a transmission line. However, it influences the practise to be followed in lightning arresters. The higher insulation of the line prevents the local relief of induced lightning strokes and therefore carries into the station unusually high lightning voltages. The choice of high factor of safety in the insulators leaves the standard circuit breaker, for example, and the current transformer, for another example, relatively poorly insulated. It is an easy matter for the transmission engineers to select a current transformer of higher voltage than usually demanded. But it is not a matter that can be so easily taken care of in the circuit breaker. The circuit breaker is a combination of a porcelain bushing, steel parts, and metal mechanism which has been standardized and is expensive and presumably already in use in this hypothetical instance. The porcelain bushings cannot be either changed or increased in dielectric strength. To place a single lightning arrester on the bus without any protection on the feeders would be tantamount to inviting the lightning to jump over the bushings of that very important protective device, the circuit breaker, and thereby invite a calamity of serious nature. Such a condition of high insulation on the line and low insulation in the breaker demands not only a lightning arrester on each feeder but also a considerable inductance in the form of choke coils between the line and circuit breaker. It also demands for the best conditions of protection that a lightning arrester be placed on the bus of the station in order to discharge the quantity of electricity which gets through the choke coils of the feeders during the brief period that most of the lightning charge is finding its way to ground through the lightning arrester. A choke coil cannot choke back the traveling wave without absorbing some of the charge. Such an absorbed charge cannot, without reflection of the wave, return to the lightning arresters on the feeders any more than a bullet can return to a rifle barrel after it has passed the muzzle without rebounding from the target. The analogy is complete. Here, then, is described the condition where if the engineer were laying out an installation in the first place he could have the choice of higher voltage circuit breakers and practically few lightning arresters or lower voltage circuit breakers and a full complement of protective apparatus. Like any other engineering proposition, all the parts must be designed to work together.

The casual critic who holds the weakness of lightning arresters reponsible for the interruption of service during lightning storms is misled by the name of this device, to wit, "lightning arresters", and is in utter confusion regarding their function. A lightning arrester is designed to protect end coil insulation from puncture and any other exterior insulation at the point where the arrester is installed. If it protects the service it is only a secondary matter due to its protection of the insulation. The most prolific cause of interruption of service on overhead lines is arc-overs of insulators by lightning at points distant from arresters. The lightning arrester has no function to prevent such an occurrence. The best protector for accidental arc-overs of insulators is the arc suppressor—a device not yet sufficiently perfected to be used in standard practise.

Prophecies. Closing this part of the subject,—this paper is not intended to give completely even the principles of protection, to say nothing of the theory and practise. It strikes a few high spots raised by the investigating committee. There must be the admission of lack of perfection in the art of protection. This admission is somewhat offset by renewed activities in researches and developments since the close of the war. It may be pertinent (although risky to the prophet) to say we can see the possible routes by which a high degree of perfection is to be attained. This statement is virtually saying that more than half the final spurt is run. Preventing interruption of service by arc-over of insulators will do away with the cause of the majority of interruptions on overhead circuits.

To clean up the final residue of failures and troubles will require the most hearty cooperation between the operating engineers and the laboratory specialists who spend their time studying the voltage phenomena and the characteristics of insulations—and will call for a power of analysis not yet in sight. For long-distance transmission the goal sought is the degree of continuity of service given by the Edison companies in the larger cities. It is possible and must be reached.

THE ALUMINUM ARRESTER AND CRITICISMS OF FILM THEORIES

One of the broad fundamentals dwelt upon in the foregoing pages is the need in an arrester of a high discharge rate, a rate comparable with the currents in lightning surges. It is not necessary to master the fine details of theories of films to determine if an arrester has this quality. Place a single cell of two cones for a unit period of one to four cycles on a 600-volt a-c. circuit of sufficient power to maintain the voltage. Does the current rise to several hundred amperes? Therein is the answer without any theory. An oscillograph gives full data on what takes place. It will give the answer, "No", to the question, "Does the arrester short-circuit the voltage?" The ballistic throw of a large ammeter, not too much damped to respond to a sixtieth of a second, will give an indication of large current flow.

Inspection and Repair of Aluminum Arresters. The question of overhauling the aluminum arresters is by far the most serious criticism that has been made of arresters. The whole subject of inspection and repair is under reconsideration. The following investigations show that the power factor of the aluminum cells, either as individual cells or as a whole stack, may be a desirable method of inspecting the condition of an arrester before deciding to disassemble the parts. The use of power factor is new and, furthermore, it is well-known that the effects given by aluminum cells, such as variations in current, wattage loss, and power factor, are factors of wide variation, depending upon the quality of the aluminum, the nature and temperature of the electrolyte, the wave form, and the like. Some cells have shown deterioration by the presence of an abnormally high charging current. (Unfortunately deterioration is not always accompanied by higher charging current.) Cells have also shown deterioration by the value of the watts loss. So far as the recent investigations have gone the power factor method seems to be the most generally reliable indication of the condition of the cells. Deductions drawn from the measurements of power factor are comparatively new and, while the figures given are actual test data, it will require a wide experience to determine on dependable instructions for making the inspection. With these words of caution against the interpretation of these favorable data as final, some excellent results of these investigations will be briefly reviewed.

The Adirondack Power Company had two 33-kv. arresters handy and of promising interest. Reliable information was received that they had not been overhauled since installation, thirteen years ago. The first point of interest was the conclusion that either the arresters must be in deplorable condition or else there was some good way of avoiding frequent overhauling. We were in search of deteriorated aluminum cones and would have been pleased to have found this condition. The operating engineer may be more pleased by the fact that the aluminum surfaces were not corroded or eaten at the contact line of oil and electrolyte. Of course, thirteen years of daily charging had partially exhausted the electrolyte. Although new electrolyte was needed the discharge rate of each cell on 600 volts was several hundred amperes, showing that the arrester still gave good protection. It was still in good operating condition. The oil was somewhat modified by the oxygen and hydrogen freed by electrolytic action, but was not in a condition risky for operation.

The second point of prime importance was the fact that the charging currents of the several phases of the arrester as read by ammeter were near normal. On the west arrester the currents were slightly below normal. On the east arrester they were only 9 per cent to 27 per cent above the recommended normal value. Wave shape, quality of aluminum, and quantity of electrolyte will make this much difference. Since other tests were made which showed the arrester needed overhauling, the results indicate the unreliability of depending on current readings alone to determine the best time to overhaul. The spark at the beginning and end of charging was snappy and normal. Here, then, was an arrester giving safe and satisfactory operation, but which had reached a point of exhaustion of electrolyte, marking the period most desirable to overhaul.

A new method of simple electrical test was adopted, which shows this deteriorated condition of the cells so strongly that it is more than 300 per cent greater than with new cells. The method consists in measuring the wattage and voltage in addition to the charging current and calculating the power factor. For example, one stack of cones on the east arrester was removed for other studies. A stack of new cones replaced it. The power factor of this new stack was 14 per cent. The three remaining stacks had power factors of 42 per cent, 46 per cent and 47 per cent. (three times normal).

The west arrester with charging currents less than normal had power factors higher and lower than the east arrester, 50 per cent, 44 per cent, 43 per cent and 27 per cent respectively for the four legs. Since no inspection of these cells has been made, other than indicated by these measurements, the physical condition of the cells of the west arrester is not yet known.

Twenty-one cells of the stack taken from a tank of the east arrester were given individually a detailed study. Such measurements were made as: (1) Initial current rush at 250 volts impressed, (2) normal charging current, (3) watts loss, (4) discharge rate at 600 volts impressed, (5) rate of dissolution, (6) power factor, (7) thickness of film, (8) restoration of normal film, (9) resistance of electrolyte, (10) quantity of electrolyte per cell, (11) concentration of electrolyte, (12) insolubility, if any, of precipitate, (13) exhaustion of electrolyte, (14) physical appearance of films and degree of corrosion of the aluminum surfaces, (15) sludge at surface of electrolyte, (16) sludge deposited on the free surface of the cones, (17) also sludge in the body of the oil, and (18) electrolyte in bottom of tank and (19) electrolyte in the oil.

Too much attention to the many details at the present moment will tend to obscure a few important results. In general the individual cells varied in their conditions. Most of them had low charging current. Three of them had currents three times normal. Three showed considerable dissolution of film and required special attention to reform them.

All of them showed relatively high power factor. The highest was 88 per cent. The lowest was 36 per cent. Several ran in the sixty-percentages. Most of them were in the forty-percentages, around the average value for the stack.

Attention was given to the typical groups of cells to determine if they could be brought back to the normal condition of new cells without disassembling. It was done simply and quickly. Electrical treatment (momentary high current rush) was given to the films and the old electrolyte was replaced by new. The power factors returned to the value for new cells. After thirteen years of continuous operation these particular cells were made as good as new without treatment with alkali or acid and without factory formation of film.

As depreciation goes on all apparatus, this record is satisfactory. So far as any one can see the aluminum is good for several decades more. It is desirable to renew the electrolyte more often than once in thirteen years, but apparently no harm has come from this long period of use. Why can not this record be extended to all installations of arresters? We can see no reason to the contrary at present. The materials in the arrester (aluminum, electrolyte and oil) seem to be the same as the average of all other arresters. The only apparent difference from standard practise is in the method of charging the cells each day. When this matter has received thorough investigation and repeated confirmation has cleared away all doubts, it will be time to make definite and final recommendations.

Before this longevity can be brought about there are many arresters in service to be overhauled. There are conditions where films are to be removed as the easiest way of removing impurities on the surface and in the cavities of the aluminum produced by the action of the modified oil. To send aluminum cones back to the factory with the expenses of express, factory labor and chemicals, and loss of time, is a serious factor and an endeavor is being made to develop methods which will avoid much of it in the future. The developments and early installations were made with aluminum formed without elaborate dipping tanks, water cooling and automatic regulation. In the routine standardization of factory processes the early art of formation was forgotten. These methods will be revived and improved so that a properly trained man may be able to reform films without loss of time at the place of installation.

To determine what approximate conditions were involved, single cells were experimented upon. The films were removed and the surfaces of the aluminum thoroughly cleaned, involving about a minute of time. After the cones were washed, the major part of the new film was put on, by the most rapid method known, in about a minute. The temperature of the electrolyte rose about 30 deg. cent. The finish was then applied by the normal charging method. Several minutes of application were used.

With suitable chemicals, machines and equipment this work may be done in the field of operation. The standard electrolyte contains a germicide and two organic chemicals which make it less suitable and more expensive for forming films than "forming" electrolyte which does not contain them. The electrolyte used in forming is more or less exhausted in the process which involves considerable electrochemical energy. This exhausted electrolyte, therefore, must be replaced by fresh electrolyte after the new films are formed.

This is not the time or place to give the detailed instruction for the proposed methods of inspecting and overhauling. If it is found desirable after further experimentation, it is planned to give instruction elsewhere—in the *G. E. Review* and in pamphlet form.

The new power factor method of inspection of the condition of an aluminum arrester may be put into the hands of any one familiar with the handling of indicating instruments around a high-tension three-phase system. The methods of renovating the films at the place of installation is simple enough to anyone accustomed to manufacturing and laboratory work. There are a few things to be scrupulously avoided. There are corrosive chemicals to be used. Furthermore, an equipment is necessary to do the work economically. There should be two trained men, such things as standard electrolyte, forming electrolyte, acid, motor-generator, standard cells for comparison, exchange racks, "forming" racks, suitable meters (ammeter, voltmeter, wattmeter), potential transformer of variable voltage, jin poles, block and tackle, rapid filter, graduates, suitable glass and rubber tubing, motor-operated contactor and so on.

There will not be enough work on any one transmission system to keep an outfit busy and to retain experts properly trained to carry on the work rapidly with accuracy and judgment. The long intervals between overhaulings allow memory to play tricks in the performance of the method. Changing personnel and positions are other factors which deprive the operator of trained men. If it could be brought about, the most economical results would be obtained by having experts with their outfit go from one system to another devoting their time to this particular work. Will a number of transmission companies share the initial expense of apparatus? With the conditions compatible with success the greatest pains will be taken by the manufacturer to give experts instruction and experience, to help them train their judgment, and to inform them on the proper instruments, apparatus, and methods to employ.

To summarize the possibilities relative to overhauling aluminum arresters, the promises are: More accurate and definite methods of inspection of the arrester will soon be made available. Unnecessary overhauling may be decreased. Longer periods between overhaulings may possibly be brought about by slight changes in methods of charging. Longer life of the arrester may also be attained. The actual cost of overhauling will be decreased. The cost per annum will be greatly decreased. Deteriorated plates may be reformed at the place of installation.

Discussion*

Joseph Slepian: Mr. Creighton has explained very clearly the necessity for a high discharge rate in lightning arresters, if any real protection to electrical apparatus is to be obtained. If this high discharge rate path is also open to normal dynamic voltage, then, as Mr. Creighton points out, the large drafts of dynamic power which must be handled by the arrester makes it too large and costly to be practical. A clear case is thus made out for the valve type of arrester.

The electrolytic arrester is the most widely used valve type and has proven its great value in service. It depends for its action on rather obscure chemical phenomena taking place in thin films on electrodes in water solutions. It has disadvantages inherent with a water electrolyte, requires frequent attention, and sometimes trouble is experienced due to its sensitiveness to chemical impurities.

The recently introduced oxide film arrester also depends for its action on the chemical and electrical properties of a thin film. This film is dry, which is an advantage but like any other solid insulation, it may be somewhat slow in its breakdown under excess potentials.

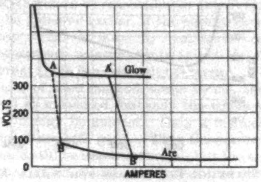

FIG. 1—ARC AND GLOW DISCHARGE

For some time past, the company with which I am associated has been working on the problem of attaining the ideal valve type arrester, from the other end. That is, instead of starting with the chemical arrester, and trying to remove its disadvantages, we start with the simple spark-gap type of arrester and try to impart to it the valve characteristic. These efforts have been successful, and, as the results are now approaching commercial form, I believe it is of sufficient interest to briefly describe the principles utilized.

To have a valve characteristic, a gap must pass current when and only when the applied voltage exceeds a definite critical value. To be of practical use for lightning arrester purposes, this critical voltage should be of the order of at least several hundred volts. Now it is known that only low-current discharges n air require such high voltages to be maintained, hence an investigation of the volt-ampere relations in low-current discharges is suggested.

Fig. 1 shows the results obtained in such an investigation. For large currents, the ordinary arc characteristic *BB'* is obtained, with voltages from 20 to nearly 100. The arc issues from a brilliant incandescent cathode spot. As the current is reduced, a point is reached, *B* in the figure, where the rate of evolution of heat is insufficient to maintain the cathode hot spot, and the voltage and current suddenly jump to values lying on another curve *AA'*. This is the volt-ampere curve of glow discharge. By water cooling the electrodes, it is possible to carry the curve

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*Includes discussion on "Questionnaire on Lightning Arrester Practice," by F. L. Hunt. (From the 1921 Annual Report of the Protective Devices Committe See A. I. E. E. TRANSACTIONS, Vol. XL. 1921, p. 837.

AA' beyond the point A, say to A', before the developing of a cathode hot spot, and the sudden dropping into the arc characteristic at B'.

In the arc there is an incandescent cathode spot with resultant vaporization of the electrode. If this hot cathode spot is prevented from forming, the discharge takes the glow form, and, with most electrodes, requires not less than 350 volts to be maintained. It is evident that a spark between cold electrodes must always start as a glow, and only after a spot on the cathode becomes sufficiently heated, does an arc form.

The curves in Fig. 1 show that it is not practical to try to get much more than 350 volts consumed in the discharge, and they also show that, if the cathode is kept cool, considerable current density may be passed still maintaining this voltage. The use of electrodes of high specific resistance offers a means for keeping the cathode surface cool for the lengths of time involved in surges on power systems. For if the resistance in series with any point is high, it is clear that the current flowing from any spot on the surface is limited, and so, too, is the heat involved. The energy in the discharge is not turned loose mostly at a small spot on the cathode, but is distributed all over the face of the electrode. Thus, no spot heats excessively, and the discharge remains in the glow form.

Having ensured that the discharge will require 350 volts for its maintenance, we must, if the desired valve characteristic is to be obtained, provide that the discharge shall also start at about 350 volts. At first sight, this seems a requirement impossible of practical attainment, because of the exceedingly minute gap necessary. But here again the high specific resistance in the electrode material comes to our aid.

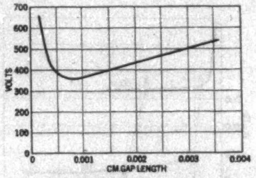

Fig. 2—Sparking Potentials for Small Air Gaps

Fig. 2 shows the relation between the spark-over potentials and gap lengths for plane electrodes, and very short gap lengths.

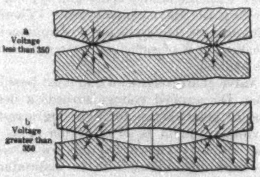

Fig. 3

It shows that the sparking potential reaches a minimum of a little over 350 volts for a gap length a little less than 0.001 centimeter, and that for smaller gap lengths, the sparking potential increases again. This may appear surprising to most of us, but it is well established by experiment.

Now suppose two disks of high-resistance material are laid one upon the other. (Fig. 3). With ordinary workmanship, the disks will make actual contact at only three or four points. Elsewhere, they will be separated by small air gaps, which may run up to three or four mils at their widest. Somewhere between the two extremes of the actual contacts, and the separation of several mils, will occur the separation of about 0.001 centimeter having the breakdown potential of about 350 volts.

When voltages less than 350 volts are applied to the disks, the current will pass only at the points of actual contact, and because of their constricted nature these current paths will be of exceedingly high resistance. Thus, very little total current will pass. (Fig. 3a). When, however, more than 350 volts is applied, the air gaps breakdown, and current is passed over the whole face of the disks. (Fig 3b). Thus, a very low over-all resistance is presented. The resistance in the electrode material forces the current to distribute itself uniformly. Hence there is no local heating, and the discharge remains in the glow form. When the voltage falls to less than 350, the discharge stops, and the current again falls to the very small value passed by the actual contacts.

To recapitulate, by the use of high-resistance electrodes, it becomes practical to use gaps so small that little more than 350 volts is required to break them down. Also the discharge which follows the breakdown is prevented by the resistance from concentrating at any point but must distribute itself over the whole face of the electrodes so that no local hot spot can form, with a resultant arc. Hence the discharge remains in the glow form, requiring over 350 volts to be maintained.

We have here then, an arrester of the valve type which has nothing whatsoever chemical in its principle of operation. It is as simple in its construction as the usual spark-gap arrester, and, in characteristics, parallels the electrolytic arrester. I believe that optimism as to the future of this device is quite justifiable.

Mr. Creighton suggests that the power factor of aluminum electrolytic arresters may be a reliable criterion of the extent of their deterioration. For several years I have been engaged in an extensive study of the power factor of aluminum cells, partly for whatever useful information might result for lightning arrester practise, and partly for the purpose of developing an electrolytic condenser for general power purposes. My experience makes me very doubtful if reliable conclusions can be drawn from the power factor as to the suitability, of a cell for lightning arrester purposes.

The electrical and chemical phenomena going on in the film on aluminum electrodes in an electrolyte are exceedingly complex, and apparently it is possible with different electrolytes to find any combination of the following properties in individual cells: 1. High power factor or low power factor. 2. Rapid dissolution or slow dissolution of film on open circuit. 3. Rapid corrosion or slow corrosion. 4. High charging current or low charging current. 5. Rapid formation of precipitates or slow formation of precipitates.

It is only the last four properties I mentioned which are significant for lightning arrester purposes, but the first is the one on which Mr. Creighton puts a lot of stress.

Actually it is possible to get any combination of all these properties in different electrolytes.

The only uniformity which I have noticed is that all cells which start with low power factor increase their power factor with time. This increase in power factor may or not may be accompanied by any considerable deterioration in respect to the properties (2), (3), (4) or (5). The only conclusion which can be drawn from high power factor is that of age, and little can be said about the properties which are more important for lightning arrester purposes.

As an example, in one electrolyte which I tried, the initial power-factor was 2½ per cent. The cell was connected permanently to the line and let run 24 hours a day. Here was a service thousands of times more severe than that which lightning arresters undergo. Nevertheless, the rise in power factor was very slow. The rise was inappreciable for the first two months, and after a year was only about 10 per cent. Judging by the power factor, here was an ideal lightning arrester electrolyte, but in respect to film dissolution, on open circuit it was quite inferior to the electrolytes now on the market.

Again, another electrolyte ran at about 6 per cent power factor, but the corrosion was so bad that the run was terminated in a few weeks. Still another electrolyte, although it gave low power factor, kept shedding precipitates of aluminum hydroxide until the cell was almost packed solid with them.

With respect to reestablishing the low power factor by electrolyte renewal, and electrode treatment, I also found matters very complex. A series of experiments indicated very clearly that the rise in power factor was due in large part to a change taking place in the film on the aluminum itself. By re-treating the aluminum in fresh electrolyte it was possible to return to the low power factor, but unless every trace of the old film had been removed, the power factor in the re-treated cell would rise again much more rapidly than it had done in the old cell. For example, if the power factor in the old cell had risen 10 per cent in a year, after re-treating the power factor would rise 10 per cent in a month or two.

I maintain therefore that great caution should be used in drawing conclusions from power factor measurements as to the suitability of aluminum cells for lightning arresters. Many tests over periods of many years will be necessary before confidence can be established in a power-factor criterion.

D. W. Roper: The great difficulty in making a few installations of a new type of arrester is in drawing correct conclusions from the results. Having attempted some investigations of lightning arresters myself and concluded that after a few years it was impossible to draw any accurate conclusions from an installation of 700 arresters, it does not appeal to me when the experience with one or two installations is used as a basis of some general conclusions on high-voltage arresters. However, if we can induce a number of engineers to cooperate in the same investigation on lightning arresters and to use the lightning arrester committee as a clearing house for *all* their information, and not selected portions of it, then we should be able, in a comparatively brief time to get some accurate conclusions.

Quite a large number of types of arresters are mentioned in one of the papers. Not all of them are mentioned. One letter tells about the horn-gap water-barrel combination successfully performing its functions. I wonder if it ever successfully performed the function of a lightning arrester.

The Standards Rules of the A. I. E. E. contain a definition of an arrester, and that is as far as the rules go, but the definition includes the requirement that it must limit the voltage across the apparatus at the time of lightning discharge. Some types of arresters accomplish that result very efficiently. The arresters which have a very large amount of resistance in series apparently do not, and in this connection, I think that some attention should be drawn to a description of the lightning generator, as it was called, in the article in the *General Electric Review* for November and December. This appeared to the speaker one of the most interesting devices brought forward in recent years for the testing of lightning arresters, and the results as given in these two papers are the results which can be used in comparing directly different types of lightning arresters. That is, the tests give a measurement of the maximum potential across the terminals of the arrester at the moment of discharge, which is exactly what is wanted, and the results obtained from that lightning machine appear to check very closely with the results of experience with the different types of arresters in service.

Referring again to the letter regarding the performing of the functions of the lightning arresters, there are quite a few types of apparatus which are called lightning arresters, and which are on the market, and some of which find a ready sale. Some of them will make a funny noise when there is a lightning discharge, and some will make quite an interesting sputtering arc, and you could make them so that they would ring a bell or operate an automatic counter, but they do not comply with the function of a lightning arrester, that is, they do not limit the voltage across the arrester at the time of discharge. I suggest that the Institute might properly take some steps to protect the smaller companies who have occasion to use lightning arresters from the assaults of the glib salesman who sells these interesting, sputtering things called arresters, and which actually serve no useful purpose except to the salesman. The Institute might properly devise a performance specification for lightning arresters, and perhaps have a classification of types which would indicate the relative value of the various types of arresters, and then such a rule, with the backing of the American Institute of Electrical Engineers, would serve, you might say, as a blue sky law to prevent the sale of these lightning announcers to people who want lightning arresters.

J. L. R. Hayden: The deterioration of the aluminum arrester apparently is due to the current passing through it. This pits the cones and changes oil and electrolyte. It causes increase of current passing through. This still further increases the deterioration.

The total current in the aluminum arrester consists of a capacity current and an emergency current. The former does not pass through but merely into the arrester, and is harmless. It is the energy current which does the harm. The energy current normally is very small, compared with the capacity current, so that the total current is mainly made up of the capacity current. Therefore the energy current may considerably increase, without showing an appreciable increase of the total current. The total current may even decrease due to some loss of electrolyte which reduced the active plate surface. It requires a very great increase of energy current to show as an increase of the total current. It would therefore be reasonable to expect that the deterioration could be detected earlier, if the energy current could be measured alone. This is done by wattmeter measurement. Possibly direct-current measurements might do the same, as with direct current there is no capacity current.

The limitations of such method seems to me, that individual cells cannot well be measured, but only the whole stack of cells. The deterioration may be uneven. Only a few cells may have deteriorated, most are still good. Then the power factor of the whole stack would still be low and normal, but the arrester would be unsafe, as the few deteriorated cells heat and arc and thereby destroy the other cells.

As this method gives the average result of the whole stack, it can be useful only if the deterioration is fairly uniform through the whole stack. How far this is the case requires further investigation.

In the *OF* arrester, such measurement of deterioration by the energy current is more feasible, as in the *OF* arrester the capacity current is small, and most of the current is energy current. It therefore is our practise in life testing of *OF* arresters, to regularly measure the current and judge the deterioration from it. Individual cells can be measured. If in the cell the current is abnormally high, then the voltage on the cell is low, if it is in series with other cells. If the energy current is abnormally low—which also is objectionable in the *OF* arrrester,—then the voltage is high. Individual cells of the *OF* arrester therefore are tested by observing whether the voltage across the cell is within the proper limits. This is done in the standard method of service testing of *OF* arresters by the use of a neon tube connected across individual cells.

W. A. Lougee: An arrester to protect must have a sufficiently high current discharge rate, that is, its internal resistance must be low. Lightning arresters are one of the very few types of electrical apparatus which can not be tested and be thoroughly understood by the purchaser, and it is on account of this unfortunate situation that many incorrect ideas are obtained, and that many inefficient lightning arresters are in use.

I would like to take up a few points mentioned in the letters quoted in Mr. Hunt's paper. The oxide film arrester is spoken of as dependent on obscure phenomena and involving the action of films of very minute dimensions; also as a hair trigger device and based on fine haired theories and obscure chemical reactions.

The best answer to all this is to state briefly the arrester's action and behavior when connected to the lightning generator that Mr. Roper mentioned.

With this apparatus, we have been able to obtain a greater discharge through an arrester than the arrester will be subjected to in actual service, outside of a direct stroke. A piece of a tree branch placed in the circuit of this lightning generator will be splintered and torn to pieces. Now if an oxide film arrester is substituted for this tree branch, and, in addition the normal voltage of the arrester be also applied directly to the terminals from a circuit of large power capacity, the high power impulse discharge is successfully taken care of. That is, not only does the impulse go through the arrester without damage to either the dynamic circuit or the arrester, but the recovery or reseal action of the arrester prevents any dynamic power following through the arrester. It is evident to withstand such punishment, the arrester must be staunch and not a hair trigger device.

Another writer mentions the fact that only one of sixteen oxide film arresters discharged. Obviously, this is absurd unless one sits by the arrester and watches it continuously as the arrester itself gives no external indication of discharges.

Lightning arresters are not hot-house plants. They are given a more severe testing in the factory than the majority of electrical apparatus and they will stand a lot of abuse.

Reference was made to the possible high time-lag of the oxide film arrester due to the fact that it consists of solid insulation. The film is solid, but at the same time it is somewhat porous. An oxide film arrester on the circuit without a series gap will pass several milli-amperes of current, and it is on this account that it has not a high time-lag.

L. R. Lee: The writer is interested in lightning arresters from the standpoint of the construction and operating engineer, and in going over this matter of arrester with users, he has found that there is, as mentioned in this paper, some lack of confidence in the use of the lightning arrester. Papers like this should help in restoring some of this lost confidence as they give the user a better insight into the functions of the arrester, the way it performs and some simple tests by which he can convince himself of the value of the arrester as a device to limit the damage that may be caused by high voltage. I think that the account given about the arrester which went some thirteen years without being opened is interesting but I doubt the advisability of giving publicity to such examples. I would much rather hear about arresters that have been systematically repaired twice a year by opening the arrester and giving thorough inspection, and how this was accomplished at small cost and little inconvenience. I believe some of the lack of confidence has been due to lack of proper maintenance.

I do not believe the construction and the operating engineer are in a position to offer any valuable suggestions as to the way arresters should be built, it is their function to see that they are properly installed and maintained. It is up to the manufacturer to collect all possible data from the operating and construction engineers as to troubles or difficulties which they may have encountered in the use of arresters and make all possible use of such data in making progress in the design of this equipment. I doubt whether there could be too much emphasis placed by the manufacturer upon the proper care of the arrester and the proper way of installing it.

It is not only important that the manufacturer point out on the wiring diagram the location for the arrester but he should also advise with the construction engineer as to the physical arrangement of the connections for the arrester, and in planning for the installation of the arrester thought should be given to any trouble which may occur from the use of the arrester and also to the accessibility and convenient arrangement that may facilitate inspection and repair.

I realize that the manufacturer has been loath to lay down too rigid rules for the maintenance of this equipment, and I realize his good intentions of working out ways of testing the equipment so that it may not be necessary to disassemble it, but it seems to me quite natural to expect confusion on the part of the operating engineer when he is told about tests which may indicate to him the condition of his arrester and at the same time told that these tests may not work and that the arrester should be overhauled in any case. I believe it would be better to spend any effort along this line towards making it easier and cheaper to open the arrester and give it thorough inspection and such repair as may be necessary.

The writer has been much pleased to note the progress being made in the oxide film type of arrester as it seems that this arrester working on a similar theory to that of the electrolytic, is a device much simpler and easier repaired and altogether seems to have many advantages.

Condenser Discharges Through a General Gas Circuit

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Review of the Subject.—*Any change in the electrical conditions of a circuit, whether internal, such as a change of load, starting and switching operations, short circuits, or external, such as due to lightning, involves a readjustment of the stored electromagnetic and electrostatic energy of the circuit, that is a so-called transient. Such transient is of the general character of a condenser discharge through an inductive circuit. The phenomenon of the condenser discharge through an inductive circuit therefore is of the greatest importance to the engineer, as the foremost cause of high-voltage and high-frequency troubles in electric circuits.*

With the development of radio communication—whether wireless or wired—the condenser discharge through an inductive circuit has assumed a great additional importance since, with the exception of a few of the highest power transoceanic stations, which use power-driven high-frequency alternators, the source of power in all radio communication is the condenser discharge through the inductive circuit, whether as a damped wave or as an undamped wave. In undamped wave radio communication, the condenser discharge circuit is coupled with a source of electric power—a battery—in such a manner, that, without interfering with the character of the oscillation, sufficient energy is fed into the circuit to maintain the oscillation, similarly as in the clock, the pendulum is coupled with a source of mechanical power—weight or spring—so as to maintain its oscillation undamped.

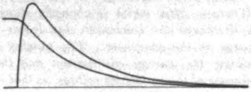

Fig. A

The condenser discharge through an inductive circuit is thus one of the most important phenomena with which the electrical engineer has to deal.

The classical equations of the condenser discharge through an inductive circuit were given a very long time ago, and are contained in all text books.

According to them, if the ohmic resistance r of the circuit is greater than a certain critical value $r_0 = 2\sqrt{\frac{L}{C}}$, *the discharge is unidirectional and non-oscillatory, that is, the voltage and current gradually die out without ever reversing in direction, and vanish, theoretically, after an infinite time, as illustrated in Fig. a for the case* $r = 1.5\, r_0$.

If the ohmic resistance r is less than the critical value r_0, *the discharge is oscillatory, that is, voltage and current perform a series of oscillations of gradually decreasing amplitude, but constant frequency, each half wave being less than the preceding one by a constant percentage, until finally, after a theoretically infinite number of half waves, the current and voltage become zero, as illustrated in Figs. b and c. Fig. b shows a rapid damping, due to the resistance of the circuit being not much less than the critical resistance,* $r = 0.5\, r_0$; *and Fig. c shows the slow damping that is, the more sustained oscillation, appearing in a low-resistance circuit,* $r = 0.1\, r_0$. *The half waves of current and of voltage are not sine waves, but are the product of a sine wave and an exponential, due to damping effect of the resistance, therefore the first part of each half wave is greater than the last part, and the maximum is not in the middle, but before the middle, as is best seen in Fig. b*

These classical equations of the condenser discharge however apply only when the resistance of the circuit is constant, or practically so, that is, when all the energy dissipation occurs in a metallic or electrolytic resistance; that is, a resistance consuming a voltage proportional to the current, and in which therefore the voltage drop in the resistance becomes zero for zero current. These classical equations however do not apply even approximately, when the resistance of the circuit is not constant but varies with the current, as is the case in a gas circuit, such as a spark gap, vacuum tube, etc., as has been pointed out before. It is rarely that the condenser discharge through an inductive circuit does not include, at least, as a part of its energy-dissipating resistance, a gas circuit.

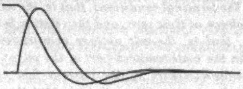

Fig. B

The usual method of producing a condenser discharge through an inductive circuit is gradually to charge a condenser from a source of electric power, until the condenser voltage has risen sufficiently high to jump a spark gap (the rotary gap, or quenched gap of the damped wave wireless for instance) and thereby discharge through the inductive circuit. In lightning disturbances of electric systems, and in high-voltage high-frequency disturbances, due to internal causes, an arc or spark discharge almost always is in circuit. The discharge of the lightning arrester which protects electric circuits, generally, occurs over a spark gap. In the production of undamped waves for radio communication, a vacuum tube is in circuit. The path of the lightning discharge in the clouds, or between clouds and ground, is entirely within the air, and the voltages and currents induced in transmission lines by the lightning flash naturally follow the voltage and current wave shape of the lightning flash, which is not that of the classical equations. A condenser discharge containing no gas path, like that of the bound charge of an overhead ground wire, set free by a cloud discharge, is rare

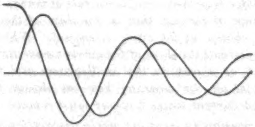

Fig. C

Obviously the larger the part of the total energy dissipation of the condenser discharge which occurs in a gas path, the more the discharge equations differ from the classical equations, so that, while the latter may give a fair approximation when the gas path constitutes only a small part of the energy dissipation, when it represents all or a large part of it, the classical equations become unsatisfactory. In view of the high industrial importance of the condenser discharge through an inductive circuit, and the relatively small amount of work done on the general equations of a condenser discharge through a non-ohmic resistance, a further study of it appears appropriate.

Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

When dealing with a non-ohmic resistance, that is, a resistance varying with the current, it usually is preferable to drop the term "resistance", and deal with the relation between the current i and the voltage E. Thus, the general differential equations of the problem are derived from the classical equations by adding a term E, which is the potential drop across the gas path, or, in general the non-ohmic resistance. This voltage E is a function of the current i, and often also of the time t—where there is a lag of the effective resistance, that is an asymmetry between rising and decreasing current. As i also is a function of the time, E is a function of the time, and can be expressed by a Fourier series (multiplied by an exponential). This gives a general differential equation, which is integrated by the product of exponential function and Fourier series, and the constants of the integral equation—the integration constants and the indeterminate coefficients of the Fourier series—then follow from the terminal conditions, that is, the values of current and condenser voltage at time zero, and the relation between E and i in the gas path, that is, the volt ampere characteristic of the gas path, as shown in the mathematical part of the paper.

The general characteristics of the current flow through a gas circuit—arc, spark, vacuum tube, etc.,—is that the effective resistance" is not constant, but varies with the current, decreases with increases of current and becomes infinite for zero current. Or, considering the relation between current and potential drop, that is, the volt-ampere characteristics of the gas path—as more satisfactory in such circuits—the current is not proportional to the voltage, but no current (except a negligible ionic current) flow until a finite voltage E_1—the ionization voltage or disruptive voltage of the gas path—is reached. Then the current begins, and with increase of current, the potential drop across the gas path either remains approximately constant (as shown in oscillograms 1 and 2, low vacuum tube), that is, the effective resistance decreases inverse proportional to the current, or the potential drop decreases with increase of current (as shown in oscillograms 3, high vacuum tube), that is, the effective resistance decreases more than inversely proportional to the current. With decrease of current, the potential drop then increases again, to the final value E_2 at zero current (E_2 usually being smaller than E_1). At the reversal of the current, the potential drop across the gas circuit thus suddenly changes, from E_2 to $-E_1$, that is, shows a discontinuous or abrupt change by $E_1 + E_2$, as shown by the oscillograms.

There can be no instantaneous voltage change at the condenser, since such would mean an instantaneous change of condenser charge, and thus an infinite current. The change of potential drop across the gas path, at zero current, thus must be neutralized by an equal but opposite instantaneous change of the inductance voltage, and as the inductance voltage is proportional to the rate of change of the current, the rate of change of current, that is, the slope of the current wave, must abruptly change at the current reversal. Wherever therefore a gas path is in circuit the slope of the current wave abruptly changes at zero current, as shown in the oscillograms and frequently observed before, though its meaning has not always been realized. The voltage and current waves however must remain continuous.

As it is not possible to integrate over a discontinuity, the integral equations of the condenser discharge through a circuit containing a gas path can apply only for one half wave of current. It therefore is not possible to get a set of equations to represent the complete discharge, but for every half wave of current of the discharge, a new set of equations applies, as shown in the numerical examples. In general the equations of discharge current and voltage are of the same form throughout, but have different constants for every half wave. The constants for the first half wave are derived from the initial terminal conditions, that is, the values of current and condenser voltage at the beginning of the discharge. The constants of the second half wave are derived from the final values at the end of the first half wave as initial values of the second half wave, and so on.

As the frequency is one of the constants derived from the terminal conditions, the different terminal conditions of the successive half waves may give different values of frequency for the different half waves of the same discharge. This is the case, and the frequency that is, the duration of the successive half waves is not the same, but the frequency decreases. In other words, the duration of the successive half waves, or the wave length, increases, especially towards the end of the discharge, as is quite noticeable in the oscillograms. This increase of wave length may be quite considerable, as much as 25 to 30 per cent for the last half wave in some of the instances given in the paper. This feature may have some bearing in damped radio telegraphy, by limiting the sharpness of the possible tuning.

With a gas path in the circuit requiring a finite voltage E_1 for the current to start, it follows that if the initial condenser voltage e_0 is greater than E_1, the discharge takes place; if e_0 is less than E_1 no discharge occurs. The classical condenser discharge equations always give a discharge, whatever may be the value of the condenser voltage e_0.

From this it also follows that the condenser discharge through a gas circuit can have only a finite number of half waves, and not an infinite number of progressively increasing values, as given by the classical equations. At every successive half wave of discharge, the condenser voltage e is less than that of the preceding half wave, due to the energy dissipation in the circuit, and therefore, at a finite number of half waves, the condenser voltage e must drop below the voltage E_1, required to initiate the current through the gas path, and then the discharge abruptly stops leaving a finite voltage e, and therefore charge, in the condenser. This may be in the same or in opposite direction to the initial charge e_0, as seen on the oscillograms and the numerical examples calculated in the paper. Thus the condenser discharge through a gas circuit consists of a finite number of half waves, after which it abruptly stops, and it does not completely discharge the condenser, but leaves a "residual" voltage and charge on the condenser. The number of half waves is less the greater the energy dissipation and the more rapid therefore the decrease of the condenser voltage, so that at high energy dissipation, only a single half wave of current may occur, as shown in some of the examples. In this case, the discharge is unidirectional, but differs from the non-oscillatory discharge of the classical equations in that the current abruptly goes down to zero and a voltage is left on the condenser, while in the classical equations the current and voltage gradually fade out.

The simplest case is a condenser discharge through an inductive circuit of negligible ohmic resistance, but containing a gas circuit in which the counter e. m. f. is constant. The gas path then acts as a constant counter e. m. f. If the initial condenser voltage is e_0, the discharge current is that of the resultant voltage $(e_0 - E)$ through an inductive circuit of negligible resistance, and is thus a sine wave. At the end of the first half wave the resultant voltage has reversed, being $-(e_0 - E)$, and with E as the counter e. m. f. of the gas path, this leaves $-(e_0 - E) + E$, or $-(e_0 - 2E)$ at the condenser. The second half wave of discharge is again a sine wave, but starting with the condenser voltage $-(e_0 - 2E)$, lower by $2E$, than the condenser voltage with which the first half wave started. Thus the resultant voltage is $-(e_0 - 2E) - E = -(e_0 - 3E)$, since during the second half wave $-E$ is the counter e. m. f. of the gas path. In this case, there is not attenuation or decay during the half wave, but the half waves are sine waves, and all the decay due to the energy dissipation in the gas path occurs discontinuously at the current reversal by the successive half waves of current and voltage being lower by a constant value.—the value due to $2E$, the voltage discontinuity at the current reversal.

It is interesting to note therefore, that no matter how high the energy dissipation in the gas path, that is, the effective resistance of the gas circuit, it has no effect whatever on making the discharge non-oscillatory, but the discharge through a gas path is always oscillatory, no matter how high the energy dissipation, Thus the lightning flash must always be oscillatory, though, if the energy dissipation is very rapid—as in the faint terminal streamers of a branch discharge— the oscillation may consist of one half wave only, as in Figs. 2(I) and 3(I) of the paper.

Such a condenser discharge through a gas circuit having a constant counter e. m. f., E, thus becomes non-oscillatory only, if in addition to the gas path, there is an ohmic resistance r in circuit greater than the critical resistance r_0 of the classical equations. Discharge waves of this character are given in Fig. 1 *(III) of the paper for the case of negligible ohmic resistance, and in Fig.* 1 *(II) if the discharge circuit contains ohmic resistance besides the gas path.*

Consider a gas circuit like that in oscillogram 3, in which the potential drop across the gas circuit decreases with increase of current, and therefore is a maximum E_1 at zero current, and a minimum E_m at high current. Then at the beginning of each half wave, the current starts at the rate of a sine wave discharge of the condenser voltage e_0 with a counter e. m. f. E_1, but with increasing current, the counter e. m. f. decreases, the more the greater the difference between E_m and E_1, and the resultant voltage $(e - E)$ thereby increases. That is the current increases at a greater rate than it would in a sine wave—the reverse of that in the classical equations— so that the first part of the current half wave is lower than the last part, and the current maximum is beyond the middle of the half wave, as shown in the oscillograms and numerical examples. That is, each half wave has the character of a cumulative oscillation, and the exponent of the exponential term is positive. (Such discharge waves are impossible with the classical equations.) Therefore, in the case of a gas path with double peaked potential drop, an attenuation occurs at the current reversal lowering the height of the following half wave below that of the preceding half wave; but in the following half wave a cumulative effect occurs and again increases the height of the half wave, Necessarily, the cumulative effect, being due to the difference $E_1 - E_m$, is less than the attenuation, which is due to E_1, so that the result is a decay of the discharge as obvious, but at a rate less than corresponds to E_1. Or, in other words, at the current reversal, an attenuation or wave decay occurs, greater than that corresponding to the energy dissipation in the circuit, and during the following half wave, a cumulative effect occurs, returning the energy and reducing the attenuation to that corresponding to the energy dissipation. The effect is then of the character of a discharge through a circuit having a constant counter e. m. f., E_1, and a negative resistance. It is interesting to note, that in such a circuit an ohmic resistance r can be inserted, equal and even greater than the critical resistance r_0 of the classical equations, and the discharge nevertheless remains oscillatory. It becomes non-oscillatory only when the ohmic resistance, inserted in series to the gas path, is greater than the sum of the critical resistance r_0 and the apparent negative resistance of the gas path.

Numerical examples of such a discharge are given in Figs. 2 *(III) and* 3 *(III) of the paper, for the case of negligible ohmic resistance, and in Figs.* 2*(I) and (II) for the case of the circuit containing ohmic, that is, constant, resistance in addition to the gas path.*

The maximum value, which the negative resistance of the gas path can reach is equal to the critical resistance r_0.

The general method of integration described in the foregoing, applies not only to symmetrical circuits, that is, gas circuits in which the potential drop for rising current is the same as for decreasing current, but also for unsymmetrical gas circuits, or circuits in which the potential drop at decreasing current is different, almost always less, than for increasing current. Examples of both types of discharge are given in the paper, Figs. 1 *and* 2 *being symmetrical, and Figs.* 3 *and* 4 *unsymmetrical discharges. As the integration takes place step by step for each half wave, the method applies equally to so-called unidirectional gas circuits, that is, gas circuits having a potential drop which for current flow in one direction is different, often very many times greater, than for current flow in the opposite direction, such as the circuit of a vacuum tube with one incandescent and one cold electrode, etc., such as so-called rectifing circuits. Examples of such are given in Fig.* 7.

To conclude then; the condenser discharge through an inductive circuit of negligible ohmic resistance, but containing a gas circuit, if always oscillatory.

The oscillation consists of a finite number of half waves, the less, the greater the energy dissipation in the gas path.

The oscillation stops abruptly, leaving a finite voltage and charge in the condenser, which may be in the same or in the opposite direction to the initial voltage.

The frequency of the successive half waves is not constant, but decreases, that is, the wave length decreases, in the successive half waves. If the potential drop across the gas circuit is constant the discharge consists of pure sine half waves. In a circuit of negligible ohmic resistance, the successive half waves decrease by a constant difference.

In such a circuit, the discharge becomes non-oscillatory only if in addition to the gas path, it contains an ohmic resistance greater than the critical resistance of the classical equations.

If the potential drop across the gas circuit decreases with increasing current, the discharge waves are cumulative, that is, the current increases during each half wave, and the decay of the wave is produced by the amplitude of the successive half waves decreasing at the current reversal, but the exponent of the exponential term is positive.

Such a circuit acts like a combination of a constant counter e. m. f. and a negative resistance.

The discharge through such a circuit becomes non-oscillatory only if, in addition to the gas circuit, it contains an ohmic resistance greater then the sum of the critical resistance of the classical equations plus the negative resistance of the gas circuit.

The condenser discharge through an inductive circuit containing in addition to an ohmic resistance a gas path, is intermediate between the discharge through a pure gas path and the classical condenser discharge equations, but always retains the characteristics of the discharge through a gas path, of a finite number of half waves, a residual charge on the condenser, a decrease of the frequency and a change and often reversal of the attenuation constant.

THE usual equations of the condenser discharge through an inductive circuit, as given in the textbooks, give an oscillation of progressively decreasing amplitude, if the circuit resistance is less, and an impulse or unidirectional discharge, if the circuit resistance is more than twice the surge impedance. They apply only for the case in which the resistance of the circuit is constant, that is, independent of the current, and therefore do not apply to the very common case in which the discharge circuit includes a spark gap or largely consists of a gas path (as is the case with the lightning flash). Experience shows that the phenomenon is essentially different; for instance, the condenser does not completely discharge, but a residual charge remains, which may be in the same, or in opposite direction to the initial charge.

A study of these more general discharge equations thus is of interest, and is given in the following in a somewhat different form from previous publications.

Let an electric circuit contain a constant capacity C, a constant inductance L, a constant ohmic resistance r, and an effective resistance r', the voltage E of which varies with the current in any desired manner:

$$E = i\,r' = f(i)$$

such as that of an arc, spark or vacuum discharge (lightning).

Characteristic of such gas or vacuum discharges is, that the voltage E does not vanish for zero current, but reaches a finite value at $i = O$, that is, the "effective resistance" r' becomes infinite at zero current. Usually, the voltage E is a maximum for zero current, and decreases with increasing current.[1]

Some approximate empirical equations which have been proposed for such discharges, are:

Gas discharge $E = r'\,i = \dfrac{a}{1 + b\,i}$;

where a = disruptive strength of residual ionization of discharge path.

Arc $E = r'\,i = e_0 + \dfrac{a\,(l + \delta)}{\sqrt{i}}$

where e_0 = terminal drop, l = length of arc, and δ = terminal effect on arc stream.

Geissler Tube $E = r'\,i =$ const.
(approximation, at fairly high gas pressures especially)

In all these cases, where the voltage E does not disappear, but reaches a finite value E_0 at zero current, it must as counter e. m. f. of energy dissipation in the discharge path, abruptly change at the current reversal, from $+E_1$ to $-E_0$, that is, the counter e. m. f. E contains a discontinuity at $i = O$.

In a circuit containing inductance and capacity, neither current nor voltage can change abruptly, that is, instantly, but both must be continuous, since a discontinuity of current would give an infinite e. m. f. of self-induction, a discontinuity of voltage an infinite capacity current. Thus the discontinuity of the counter e. m. f. of the discharge path must be compensated by an equal and opposite discontinuity of the counter e. m. f. of self-induction, that is by a discontinuity in the slope of the current wave.[2]

Due to the discontinuity of the slope of the current wave at the current reversal, the integration cannot be carried over the current reversal, but a different set of integral equations applies to each half wave of current. The integral equations of the successive half waves usually have the same form, but differ from each other by their integration constants derived from the terminal conditions: The initial terminal conditions of each half wave being the final terminal conditions of the preceding half wave.

GENERAL CASE

The differential equations of the discharge of a condenser of constant capacity C and initial voltage e_0, through a constant inductance L, a constant resistance r, and a circuit of counter e. m. f. $E = f\,(i)$, (lightning flash, Leyden jar discharge), are then given by:

Voltage at condenser terminals

$$e = L\frac{d\,i}{d\,t} + r\,i + E \qquad (1)$$

Current in discharge circuit

$$i = C\frac{d\,e}{d\,t} \qquad (2)$$

with the terminal conditions

$$t = 0\,; \qquad i = 0\,; \qquad e = e_0 \qquad (3)$$

Differentiating (1) and substituting (2), therein, gives

$$L\frac{d^2\,i}{d\,t^2} + r\frac{d\,i}{d\,t} + i/C + \frac{d\,E}{d\,t} = 0 \qquad (4)$$

As i is a function of t, $E = f\,(i)$ may be expressed as a function of time

$$E = f\,(i) = f'\,(t)$$

and in the interval between two successive zero values of i, $f\,(i)$ can thus be expressed by a Fourier series of t.

Instead of expressing $f\,(i)$, without loss of generality, the function

$$F\,(t) = \epsilon^{ct}\,(B_0 - f\,(i)\,) \qquad (5)$$

can be expressed in a Fourier series, where c is still an arbitrary constant, and B_0 chosen so that $f\,(i)$ has no constant term.

This gives

$$\begin{aligned} E &= f\,(i) = B_0 - \epsilon^{-ct}\,F\,(t) \\ &= B_0 - \epsilon^{-ct}\,\Sigma\,\{B_k \sin k\,q\,t + B_k' \cos k\,q\,t\} \qquad (6) \end{aligned}$$

where c is an exponential decrement, and q the wave length constant, that is, $q\,t = \pi$ gives the interval between two successive zero values of current. c and q appear as integration constants.

[Equation (5) excludes the case of the impulsive discharge, in which the current reaches zero only after infinite time, as occurs for $f\,(i) = 0;\, r \gtrapprox 2\,\sqrt{L/C}$. This case is of no importance here.]

In view of equation (6), (4) is integrated by

$$i = \epsilon^{-ct}\,\Sigma\,\{\,A_k \sin k\,q\,t + A_k' \operatorname{cost} k\,q\,t\,\} \qquad (7)$$

As the integration is carried over one half wave only, we can, without loss of generality, assume the trigonometrical part of the second half wave of (8) and (7) as symmetrical with that of the first half wave, that is, (7) and (8) to contain only the odd harmonics: $k = 2\,i + 1$

Substituting (6) and (7) into (1) and (4) gives

$$\begin{aligned} e = B_0 + \epsilon^{-ct}\,\Sigma\,\{\,&[A_k\,(r - c\,L) - k\,q\,L\,A_k' \\ &- B_k] \sin k\,q\,t + [k\,q\,L\,A_k + A_k'\,(r - c\,L) \\ &- B_k'] \cos k\,q\,t\} \qquad (8) \end{aligned}$$

$$\epsilon^{-ct}\,\Sigma\,\{\,[A_k\,(1/C - c\,r - L\,[k^2\,q^2 - c^2])$$

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[1] In some conductors, with increasing current, the voltage E reaches a minimum, and then increases again with further increase of current. (pyro-electric conductors.)

[2] Such discontinuities of the slope of the current wave are shown by the oscillograph in circuits containing such conductors, as those of rectifiers, circuit breakers, etc. For some such oscillograms, see "Transient Phenomena," II Section, in the chapter on arc rectification. Also see the following oscillograms, **Figs. 8 to 10.**

$$- k\,q\,A_k'\,(r - 2\,c\,L) + (c\,B_k + k\,q\,B_k')]\sin k\,q\,t$$
$$+ \{k\,q\,A_k\,(r - 2\,c\,L) + A_k'\,(1/C - c\,r$$
$$- L\,[k^2 q^2 - c^2]\,) - (k\,q\,B_k - c\,B_k')\,]\cos k\,q\,t\} = 0 \tag{9}$$

$t = 0$ gives the terminal conditions; $i = 0$; $e = e_0$; thus, substituting into (7) and (8)

$$\Sigma\,A_k' = 0 \tag{10}$$

$$e_0 - B_0 = \Sigma\,\{k\,q\,L\,A_k + A_k'\,(r - c\,L) - B_k'\}$$

and by (10)

$$e_0 - B_0 = \Sigma\,\{k\,q\,L\,A_k - B_k'\} \tag{11}$$

As equation (9) must be an identity, its individual coefficients must vanish. This gives the $2\,n$ equations [where n = number of harmonics of the series in (6) and (7)]

$$\left.\begin{array}{l} A_k\,(1/C - c\,r - L\,[k^2 q^2 - c^2]\,) \\ - k\,q\,A_k'\,(r - 2\,c\,L) + c\,B_k + k\,q\,B_k' = 0 \\ k\,q\,A_k\,(r - 2\,c\,L) + A_k'\,(1/C - c\,r \\ \qquad - L\,[k^2 q^2 - c^2]\,) - k\,q\,B_k + c\,B_k' = 0 \end{array}\right\} \tag{12}$$

If the relation between the current i and the potential drop E across the gas circuit, is given by an equation

$$E = f\,(i) \tag{13}$$

then, substituting for E and for i the equations (6) and (7) into (13), gives an identity in $\sin k\,q\,t$, $\cos k\,q\,t$ and the constant term, and their individual coefficients must vanish. This gives $(2\,n + 1)$ further equations.

If the relation between E and i is given empirically, by curve or table, $(2\,n + 1)$ corresponding values may be chosen and so give the second set of $(2\,n + 1)$ terminal equations.

The $2\,n$ equations (12), the $(2\,n + 1)$ equations derived from (13), and the two equations (10) and (11) give a total of $(4\,n + 3)$ equations, for the determination of the $4\,n + 3)$ integration constants A_k, A_k', B_k, B_k', B_0, c and q.

A. CONSTANT RESISTANCE

If the resistance of the discharge circuit is constant, $= r$, that is, $E = 0$; B_0, B_k, and B_k' vanish, and by (12), all the A_k and A_k' also vanish, that is, there is no discharge, unless in one of the A_k, A_k' the individual coefficients in (13) vanish, and this A_k and A_k' thus becomes indefinite.

Assume this to be the case for $k = 1$. This assumption leaves the conditions general, as by choosing another value of k, the k merely enters as a factor into the q.

We have then, for $k = 1$, by equation (12)

$$1/C - c\,r - L\,(q^2 - c^2) = 0$$
$$r - 2\,L = 0$$

thus

$$\left.\begin{array}{l} c = \dfrac{r}{2\,L} \\[2ex] q = \sqrt{\dfrac{1}{L\,C} - \dfrac{r^2}{4\,L^2}} \end{array}\right\} \tag{14}$$

by (10), $A' = 0$, and by (11)

$$A = \frac{e_0}{q\,L}$$

thus

$$\left.\begin{array}{l} i = \dfrac{e_0}{q\,L}\,\epsilon^{-\frac{r}{2L}t}\,\sin q\,t \\[2ex] e = e_0\,\epsilon^{-\frac{r}{2L}t}\left\{\cos q\,t + \dfrac{r}{2\,q\,L}\sin q\,t\right\} \end{array}\right\} \tag{15}$$

These are the well-known equations of the condenser discharge through a circuit of constant resistance, inductance and capacity.

The ratio of the values of two successive half waves is constant

$$i_2/i_1 = \epsilon^{-\frac{r\pi}{2qL}} \tag{16}$$

that is, the discharge decreases in constant geometrical proportion.

An instance is plotted as curve I of Fig. 1, for the constants

$C = 10^{-6}$; $L = 10^{-2}$; $r = 50$; $e_0 = 20{,}000$, giving the equations:

Discharge Current

$$i = 207\,\epsilon^{-2500\,t}\sin 9685\,t$$

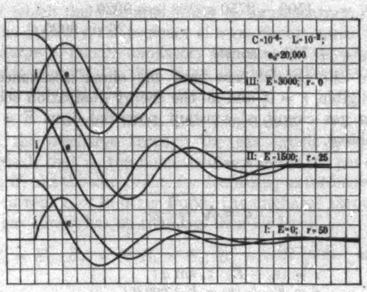

FIG. 1

Condenser Voltage

$$e = 20{,}000\,\epsilon^{-2500\,t}\,\{\cos 9685\,t + 0.258\sin 9685\,t\}$$

B. CONSTANT VOLTAGE DROP IN GAS CIRCUIT

$$E = \text{constant} = E_0$$

This gives $B_0 = E_0$; $B_k = 0 = B_k'$

Thus by the same reasoning, equation (12) gives

$$c = \frac{r}{2\,L}$$

$$q = \sqrt{\frac{1}{L\,C} - \frac{r^2}{4\,L^2}}$$

By (10); $A = 0$

and by (11) $A = \dfrac{e_0 - E_0}{q\,L}$

Thus

$$\left.\begin{aligned} i &= \frac{e_0 - E_0}{q\,L}\,\epsilon^{-\frac{r}{2L}t}\sin q\,t \\ e &= E_0 + (e_0 - E_0)\,\epsilon^{-\frac{r}{2L}t}\left\{\cos q\,t \right. \\ &\qquad \left. + \frac{r}{2\,q\,L}\sin q\,t\right\} \end{aligned}\right\} \tag{17}$$

An instance is plotted as curve II, Fig. 1, for the constants

$C = 10^{-6}$; $L = 10^{-2}$; $r = 25$; $E = 1500$; $e_0 = 20{,}000$ giving the equations

$$\begin{aligned} i_1 &= 186.4\,\epsilon^{-1250t}\sin 9920\,t \\ i_2 &= -\,123\,\epsilon^{-1250t}\sin 9920\,t \\ i_3 &= +\,70.6\,\epsilon^{-1250t}\sin 9920\,t \\ i_4 &= -\,27.7\,\epsilon^{-1250t}\sin 9920\,t \\ i_5 &= 0 \\ e_1 &= 1500 + 18{,}500\,\epsilon^{-1250t}\{\cos 9920\,t \\ &\qquad + .126\sin 9920\,t\} \\ e_2 &= -\,1500 - 12{,}200\,\epsilon^{-1250t}\{\cos 9920\,t \\ &\qquad + .126\sin 9920\,t\} \\ e_3 &= +\,1500 + 7000\,\epsilon^{-1250t}\{\cos 9920\,t \\ &\qquad + .126\sin 9920\,t\} \\ e_4 &= -\,1500 - 2750\,\epsilon^{-1250t}\{\cos 9920\,t \\ &\qquad + .126\sin 9920\,t\} \\ e_5 &= +\,760 = \text{const.} \end{aligned}$$

In the special case that the ohmic resistance is negligible, $r = 0$, and all the energy dissipation occurs in a gas circuit of constant potential drop $E = E_0$, we have,

$$\left.\begin{aligned} c &= 0 \\ q &= \sqrt{\frac{1}{L\ C}} \end{aligned}\right\}$$

thus

$$\left.\begin{aligned} i &= (e_0 - E_0)\,z_0 \sin q\,t \\ e &= E_0 + (e_0 - E_0)\cos q\,t \end{aligned}\right\} \tag{18}$$

where

$z_0 = \sqrt{L/C}$ = surge impedance, or natural impedance of the circuit

In this case, at the end of the first half wave, we have,

$$e = e_1 = -\,(e_0 - 2\,E_0)$$

and the second half wave is given by

$$\left.\begin{aligned} i_2 &= -\,(e_0 - 3\,E_0)\,z_0 \sin q\,t \\ e_2 &= -\,E_0 - (e_0 - 3\,E_0)\cos q\,t \end{aligned}\right\} \tag{19}$$

In this case, the difference between the maximum values of two successive half waves is constant:

$$\begin{aligned} e_1 - e_2 &= 2\,E_0 \\ i_1 - i_2 &= 2\,z_0\,E_0 \end{aligned} \tag{20}$$

that is, the discharge decreases in constant *arithmetical* porportion.

An instance is plotted as curve III of Fig. 1, for the constants:

$C = 10^{-6}$; $L = 10^{-2}$; $r = 0$; $E = 3000$; $e_0 = 20{,}000$, giving the equations:

$$\begin{aligned} i_1 &= 170\sin 10{,}000\,t \\ i_2 &= -\,110\sin 10{,}000\,t \\ i_3 &= +\,50\sin 10{,}000\,t \\ i_4 &= 0 \\ e_1 &= 3000 + 17{,}000\cos 10{,}000\,t \\ e_2 &= -\,3000 - 11{,}000\cos 10{,}000\,t \\ e_3 &= +\,3000 + 5000\cos 10{,}000\,t \\ e_4 &= -\,2000 = \text{const.} \end{aligned}$$

If $\quad e_0 = 2\,p\,E_0 \pm e_0{}'$ **(21)**

where p is the largest integer by which $2\,E_0$ divides into e_0, and leaves $e_0{}'$ numerically (irrespective of the sign) less than E_0, that is, $e_0{}'^2 \leqq E_0{}^2$, p is the number of successive half waves of the discharge, and $\pm\,e'_0$ is the residual charge, remaining in the condenser, after the discharge stopped. That is, in this case, the condenser discharge does not consist of a (theoretically) infinite number of gradually decreasing half waves, which completely discharge it, but the discharge stops after a finite number of half waves, and does not completely discharge the condenser, but leaves a residual charge (as well-known in the discharges of condensers, such as Leyden jars, through a spark). This residual charge may be in the same direction or in the reverse direction of the initial charge e_0.

Thus in this case, the total discharge, $\int i\,d\,t = \theta$, is not constant and equal to the charge of the condenser: $\theta_0 = e_0\,C$, but may be more or less.

If $E_0 = > e_0/3$, only one half wave of discharge occurs, and the discharge thus is unidirectional, showing a similarity to the impulsive discharge. It differs therefrom by terminating sharply at a definite time, while the impulsive discharge tapers into infinity.

In the general case B, essentially the same conditions pertain; a finite number of half waves, and a residual charge remaining in the condenser. The decrement is neither geometrical (logarithmic) nor arithmetical.

C. SINE WAVE DISCHARGE

It is of special interest to investigate the conditions under which the successive half waves of discharge current and voltage are pure sines (except as regards to the exponential factor, and the discontinuity of the current slope), that is free of higher harmonics.

Then the trigonometric series ends with $k = 1$, and it is

$$i = A\,\epsilon^{-ct}\sin q\,t \tag{22}$$

$$E = B_0 - \epsilon^{-ct}\{B_1 \sin q\,t - B_1{}'\cos q\,t\} \tag{23}$$

$$e = B_0 + \epsilon^{-ct}\{[A\,(r - c\,L) - B_1]\sin q\,t + [A\,q\,L + B_1{}']\cos q\,t\} \tag{24}$$

[For convenience, the sign $B_1{}'$ has been chosen negative, so as to make $B_1{}'$ positive for the usual form of the gas discharge.]

$2\,n + 1 = 3$ constants can then be chosen arbitrarily, that is, by experiment, etc., in the relation between i and E.

As such the following are preferably chosen:

The potential drop across the gas circuit at zero current at the beginning of the discharge: $E = E_0$ for $t = 0, i = 0$.

The potential drop across the gas circuit at zero current at the end of the discharge: $E = E_1$ for $q\,t = \pi, i = 0$.

The potential drop across the gas circuit for (approximately) maximum current, at the middle of the discharge: $E = E_m$ for $q\,t = \pi/2, i = i_m$.

In general, $E_m \leqq E_1 \leqq E_0$

This gives the equations, by substituting into (23)

$$\left.\begin{aligned} E_0 &= B_0 + B'_1 \\ E_1 &= B_0 - \delta^2 B_1' \\ E_m &= B_0 - \delta\, B_1 \\ \text{where}\quad \delta &= \epsilon^{-c\pi/2q} \end{aligned}\right\} \qquad (25)$$

thus

$$\left.\begin{aligned} B_0 &= \frac{\delta^2 E_0 + E_1}{1 + \delta^2} \\ B_1 &= \frac{B_0 - E_m}{\delta} = \frac{\delta^2 E_0 + E_1 - (1 + \delta^2)\, E_m}{\delta\,(1 + \delta^2)} \\ B_1' &= \frac{E_0 - E_1}{1 + \delta^2} \end{aligned}\right\} \qquad (26)$$

from equation (11) follows,

$$e_0 - B_0 = q\,L\,A + B_1'$$

$$\left.\begin{aligned} \text{thus}\qquad A &= \frac{e_0 - B_0 - B_1'}{q\,L} = \frac{B}{q\,L} \\ \text{where}\qquad B &= e_0 - E_0 \end{aligned}\right\} \qquad (27)$$

the equations (12) give,

$$\left.\begin{aligned} A\,[L\,(c^2 - q^2) - r\,c + 1/C] + [c\,B_1 - q\,B_1'] &= 0 \\ A\,q\,[r - 2\,c\,L] - [q\,B_1 + c\,B_1'] &= 0 \end{aligned}\right\}$$

and denoting,

$$\left.\begin{aligned} \frac{r}{L} &= a \\ \frac{1}{L\ C} &= k^2 \end{aligned}\right\} \qquad (28)$$

and substituting (27) for A, we have,

$$\left.\begin{aligned} B\,(c^2 - q^2 - c\,a + k^2) + q\,(c\,B_1 - q\,B_1' &= 0 \\ B\,(a - 2\,c) - (q\,B_1 + c\,B_1') &= 0 \end{aligned}\right\} \qquad (29)$$

From these two equations (29) follow the values of c and q, and thereby all the constants in i and e are evaluated.

As c and q enter into B_1 and B_1', through δ, equations (29) are best evaluated by approximation. That is, from (29) it follows that,

$$q = \frac{a\,B\,B_1}{B_1^2 + (2\,B + B_1')^2} + \sqrt{\frac{k^2\,B\,(2\,B + B_1')^2}{(B + B_1')\,[B_1^2 + (2\,B + B_1')^2\,]} + \left(\frac{a\,B\,B_1}{B_1^2 + (2\,B + B_1')^2}\right)^2 - \frac{a^2\,B^2}{B_1^2 + (2\,B + B_1')^2}} \qquad (30)$$

$$c = \frac{a\,B - q\,B_1}{2\,B + B_1'} \qquad (31)$$

Assuming first $q = k$ and $c = 0$, gives a first approximation of B_1 and B_1', and with these values of B and B_1', by equations (30) and (31) a first approximation of q and c is calculated, and this used in the same manner to get a second approximation of B_1 and B_1', and of q and c, and so on, until the approximation is sufficiently close, and this is usually obtained very rapidly.

IMPULSIVE DISCHARGE

Here q becomes imaginary, and the discharge thereby ceases to be oscillatory and becomes impulsive, when the term under the square root in (30) becomes negative.

This is the case for

$$a^2 > k^2 \frac{B_1^2 + (2\,B + B_1')^2}{B\,(B + B_1')} \qquad (32)$$

$$\text{or}\qquad r > 2\,z_0\,\sqrt{1 + \frac{B_1^2 + B_1'^2}{4\,B\,(B + B_1')}} \qquad (33)$$

for $B_1 = 0$, $B_1' = 0$, this gives the usual equation: $r > 2\,z_0$.

In general, in a gas circuit B, B_1 and B_1' are positive, and thus the energy dissipation that occurs in the gas circuit does not lower the values of the ohmic resistance r, at which the discharge ceases to be oscillatory, but on the contrary, the presence of a gas circuit causes the discharge to remain oscillatory for values of the ohmic resistance r, greater than those at which otherwise the discharge would become impulsive.

SYMMETRICAL GAS DISCHARGE

If the discharge through the gas circuit is symmetrical, that is, the potential drop across the gas circuit, E, has the same value for decreasing as for increasing current i, or in other words, the discharge through the gas circuit has no time lag, then we have,

$$E_1 = E_0;\ B_1' = 0;\ B_0 = E_0;\ B_1 = \frac{E_0 - E_m}{\delta},$$

and

$$q = k\,\sqrt{\left\{\frac{1}{1 + \left(\frac{B_1}{2\,B}\right)^2} - \frac{a^2}{4\,k^2}\,\frac{1}{\left[1 + \left(\frac{B_1}{2\,B}\right)^2\right]^2} + \frac{a}{2}\,\frac{\frac{B_1}{2\,B}}{1 + \left(\frac{B_1}{2\,B}\right)^2}\right\}} \qquad (34)$$

$$c = \frac{a}{2} - q\,\frac{B_1}{2\,B} = \frac{a}{2}\,\frac{1}{1 + \left(\frac{B_1}{2\,B}\right)^2} - k\,\frac{B_1}{2\,B}\sqrt{\frac{1}{1 + \left(\frac{B_1}{2\,B}\right)^2} - \frac{a^2}{4\,k^2}\,\frac{1}{\left[1 + \left(\frac{B_1}{2\,B}\right)^2\right]^2}} \qquad (35)$$

$$\left.\begin{aligned} i &= \frac{e_0 - E_0}{q\,L}\,\epsilon^{-ct}\sin q\,t \\ E &= E_0 - (E_0 - E_m)\,\epsilon^{-ct + c\pi/2q}\sin q\,t \\ e &= E_0 + \epsilon^{-ct}\Big\{(e_0 - E_0)\cos q\,L \\ &+ \left[\frac{r\,(e_0 - E_0)}{2\,q\,L} - \frac{E_0 - E_m}{2\,\delta}\right]\sin q\,L\Big\} \end{aligned}\right\} \quad (36)$$

Discharge with Negligible Ohmic Resistance

If the ohmic resistance of the discharge circuit is negligible, $r = 0$, that is, all the energy dissipation occurs in the gas circuit (as is probably usually the case with a lightning discharge, etc.), we have,

$$a = 0$$

$$\frac{c}{q} = \frac{-B_1}{2B + B_1}$$

$$q =$$

$$k\,(2B + B_1')\sqrt{\frac{B}{(B + B_1')\,[B_1^2 + (2\,B + B_1')^2\,]}} \quad (37)$$

$$c = -\,k\,B_1\sqrt{\frac{B}{(B + B_1')\,[B_1^2 + (2\,B + B_1')^2\,]}} \quad (38)$$

that is, the exponent of the exponential term is positive, and the oscillation cumulative, thus increasing during the half wave—to drop however again discontinuously at the end of the half wave—to a value less than the preceding half wave, giving the decay of discharge, by the discontinuous voltage change at the current reversal, from $+E_1$ to $-E_0$.

In the condenser discharge through a constant ohmic resistance r, the exponent of the exponential term is,

$$c = \frac{r_0}{2\,L}$$

where r_0 = ohmic resistance.

Substituting in (**38**),

$$c = \frac{r_0}{2\,L}\,, \qquad k = \frac{1}{\sqrt{L\,C}}\,, \text{ gives,}$$

$$r_0 =$$

$$-\,\frac{2}{\sqrt{L\,C}}\,B_1\sqrt{\frac{B}{(B + B_1')\,[B_1^2 + (2\,B + B_1')^2\,]}} \quad (39)$$

The gas discharge acts like an effective negative resistance of value r_0.

Symmetrical Gas Discharge of Negligible Ohmic Resistance

If the gas discharge is symmetrical, that is, in a symmetrical gas discharge of negligible ohmic resistance we have,

$r = 0$; $a = 0$, and $E_1 = E_0$, $B_1' = 0$; $B_0 = E_0$;

$$B_1 = \frac{E_0 - E_m}{\delta}\,,$$

and,

$$q = \frac{k}{\sqrt{1 + \left(\frac{B_1}{2\,B}\right)^2}}$$

$$= \frac{1}{\sqrt{L\,C\left(1 + \frac{E_0 - E_m}{2\,\delta\,(e_0 - E_0)}\right)^2}} \quad (40)$$

$$c = -\,\frac{k\,\frac{B_1}{2\,B}}{\sqrt{1 + \left(\frac{B_1}{2\,B}\right)^2}} = -\,\frac{E_0 - E_m}{2\,\delta\,(e_0 - E_0)}\,q \quad (41)$$

In this case, q is always real. Such a condenser discharge through a circuit of negligible ohmic resistance, but containing a symmetrical gas path, is always oscillatory, never impulsive, that is, unidirectional, though the oscillation may comprise one half wave only.

Decrement and Frequency

As a gas circuit acts like an effective negative resistance, it follows that in the circuit of a condenser discharged through a gas circuit a considerable ohmic resistance r_1 may exist, and the decrement of the circuit still be zero: $c = 0$.

The conditions of such a circuit of zero logarithmic decrement are,

$$c = 0; \quad \delta = 1.$$

$B = e_0 - E_0$; $B_0 = 1/2\,(E_0 + E_1)$; $B_1 = 1/2\,(E_0 + E_1 - 2\,E_m)$; $B_1' = 1/2\,(E_0 - E_1)$:

From (**31**) it follows that

$$q = a\,\frac{B}{B_1}$$

and, substituting this into (**30**), gives,

$$a = k\,\frac{B_1}{\sqrt{B\,(B + B_1')}}$$

$$q = \frac{k}{\sqrt{1 + \frac{B_1'}{B}}}$$

thus

$$r_1 = z_0\,\frac{E_0 + E_1 - 2\,E_m}{\sqrt{2\,(e_0 - E_0)\,(2\,e_0 - E_0 - E_1)}} \quad (42)$$

$$q = \frac{q_0}{\sqrt{1 + \frac{E_0 - E_1}{2\,(e_0 - E_1)}}} \quad (43)$$

where

$$z_0 = \sqrt{L/C}$$

$$q_0 = \frac{1}{\sqrt{L\,C}}$$

Thus, if in a condenser discharge circuit containing a gas path, the ohmic resistance $= r_1$ (**42**), the exponential decrement is zero, and the half waves of discharge are perfect sines. If the ohmic resistance r of the circuit is greater than r_1, $r > r_1$, the logarithmic decrement is positive, that is, the wave decays. If the ohmic resistance r of the circuit is less than r_1, $r > r_1$, the logarithmic decrement is negative, that is cumulative, and the wave increases—to decrease however discontinuously at the end of the half wave by the change of the potential drop across the gas path, at the current reversal, from E_1 to $-E_0$.

For a symmetrical gas discharge we have, $E_1 = E_0$; $B_1' = 0$, thus,

$$r_1 = z_0 \frac{E_0 - E_m}{e_0 - E_0} \tag{44}$$

$$q = q_0 = \frac{1}{\sqrt{LC}} \tag{45}$$

It is interesting to note that, when the logarithmic decrement of the discharge oscillation disappears, due to the effective negative resistance of the gas path compensating for the constant ohmic resistance of the circuit, the frequency of the discharge—as given by $q = 2\pi f$—only then becomes equal to that of the circuit without energy dissipation, when the discharge is symmetrical. If however the gas circuit is not symmetrical, but the potential difference for rising current is greater than for decreasing current, in other words, if a time lag exists in the gas path, then the frequency of the oscillation is lowered by the asymmetrical nature of the gas path (**43**).

As the decrement c and the frequency constant q depend not only on the constants of the circuit and the gas path, but also on the initial condenser voltage e_0, it follows, that for the successive half waves of such a discharge, the decrement c and the frequency constant q are different. The value of c changes from positive to negative and increases negatively, that is, the damping effect of the successive half waves decreases, is replaced by a cumulative effect, and the latter indefinitely increases, until the discharge stops. The frequency in the successive half waves of discharge decreases, that is, the wave length increases, especially towards the end of the discharge, as seen from the illustration given below, and their equations, and the appended oscillograms.

MAXIMUM INCREMENT

In a condenser discharge through a gas circuit, the exponent of the decrement ϵ^{-ct} may be positive, ϵ^{+ct}, that is, the discharge is cumulative. The question arises under which conditions this cumulative effect is a maximum, that is, when c is a maximum negative value.

Equation (**31**) shows that this is the case for $a = 0$, that is, when $r = 0$, or there is no ohmic resistance, as was to be expected.

In this case we have,

$$c = -q \frac{B_1}{2B + B_1'}$$

thus, c is a maximum for $B_1' = 0$, or $E_1 = E_0$, a symmetrical discharge.

The maximum cumulative effect should occur with the symmetrical gas discharge of negligible ohmic resistance.

We have, then from (**41**)

$$c = -k \frac{\dfrac{B_1}{2B}}{\sqrt{1 + \left(\dfrac{B_1}{2B}\right)^2}}$$

$$= -\frac{\dfrac{E_0 - E_m}{2\delta(e_0 - E_0)}}{\sqrt{1 + \left(\dfrac{E_0 - E_m}{2\delta(e_0 - E_0)}\right)^2}} \tag{46}$$

which increases with increasing E_0 and decreasing E_m.

That is, the cumulative exponential decrement due to a gas path is the larger, the larger the potential drop across the gas path at zero current, and the smaller is the potential drop at maximum current, and approaches the final value for $E_m = 0$ and $E_0 = e_0$, of $c = -q_0$, or $r_0 = -z_0$.

That is, the effective negative resistance of the gas path approaches, as a maximum, the value of the surge impedance $z_0 = \sqrt{L/C}$ of the circuit.

IMPULSIVE DISCHARGE

The question arises, whether, and under what conditions the condenser discharge through a gas circuit may cease to be oscillatory, and becomes impulsive or unidirectional.

If, as is usually the case in a gas circuit, $e_0 > E_0 > E_1 > E_m$, B, B_1 and B_1' are positive, and by equation (**33**) the ohmic resistance r is given, which must be exceeded by the circuit, to become non-oscillatory, and this ohmic resistance is greater than in the absence of a gas path.

The further question arises, whether any condition of a gas circuit can be conceived, in which the discharge becomes impulsive by the energy dissipation in the gas circuit, irrespective of the ohmic resistance of the rest of the circuit. That is, whether a condenser discharge through a gas circuit of negligible constant ohmic resistance, but high energy dissipation in the gas path—such as a lightning flash—can ever be non-oscillatory.

If the ohmic resistance of the circuit is negligible, $r = 0$, and we have from (**37**),

$$q = \frac{k(2B + B_1')}{\sqrt{B_1^2 + (2B + B_1')^2}} \sqrt{\frac{B}{B + B_1'}}$$

$$c = -q \frac{B_1}{2B + B_1'}$$

q then can only become imaginary, that is, the discharge non-oscillatory, if

$$\frac{B}{B + B_1'}$$

becomes negative.

If $B_1' = 0$ in a symmetrical gas circuit, this is not possible, but

$$\sqrt{\frac{B}{B + B_1'}} = 1\,,$$

and, as stated after equation (**41**), such a discharge through a symmetrical gas circuit always is oscillatory, no matter how high the energy dissipation in the gas circuit, unless it is made non-oscillatory by constant series resistance (**33**).

The only condition, under which such a condenser discharge through a gas circuit of negligible ohmic resistance ceases to be oscillatory occurs when B_1' is negative and $-B_1' > B$, that is, by (**26**) and (**27**):

$$\frac{E_1 - E_0}{1 + 2\,\delta} > e_0 - E_0$$

Since $E_1 > e_0 + \delta^2\,(e_0 - E_0)$

and as $E_0 < e_0$, otherwise the discharge would not start, it would mean a gas path in which the potential drop at the beginning of the discharge starts, for zero current, with a value E_0 less than the condenser voltage e_0, then decreases to E_m, and then increases to a value E_1, higher than the initial condenser voltage. In this case the discharge would obviously cease. It might be possible to experimentally create such conditions, by a slow vacuum discharge, producing a gas pressure and thereby increasing its potential drop, but in general, such would not occur. Unless a constant ohmic resistance of sufficiently high value is in series, a discharge through a gas circuit, such as a lightning flash, always must be oscillatory, no matter how great the energy dissipation, though the oscillation may contain one half wave only.

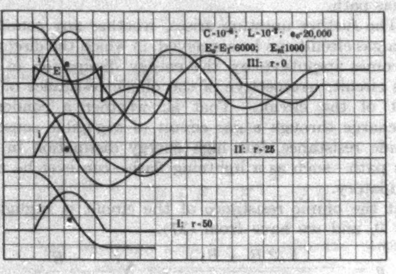

Fig. 2

Numerical Examples

As illustrations the following examples are given of some numerical values in Figs. 2 to 4, of the successive half waves of discharge, for the constants,

$$C = 10^{-6}; \qquad L = 10^{-2}; \qquad e_0 = 20{,}000$$

and in Fig. 2 for a symmetrical gas circuit varying from 6000 volts at zero current, to 1000 volts in the middle of the current wave, and back to 6000 volts at zero current, and for the three values of constant ohmic resistance.

Curve I. $r = 50$ ohms.

$i_1 = 146\,\epsilon^{-600t} \sin 9600\,t$

$i_2 = 0$

$e_1 = 6000 + \epsilon^{-600t}\,\{900 \sin 9600\,t + 14{,}000 \cos 9600\,t\}$

$e_2 = -5500 = \text{const.}$

$E_1 = 6000 - 5520\,\epsilon^{-600t} \sin 9600\,t$

$E_2 = 0$

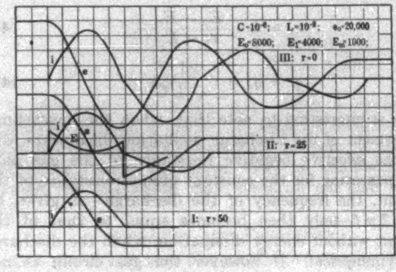

Fig. 3

Curve II. $r = 25$ ohms.

$i_1 = 140\,\epsilon^{+435t} \sin 10{,}000\,t$

$i_2 = -39.3\,\epsilon^{+2780t} \sin 9900\,t$

$i_3 = 0$

$$e_1 = 6000 + \epsilon^{+435t}\,\{-570 \sin 10{,}000\,t + 14{,}000 \cos 10{,}000\,t\}$$

$$e_2 = -6000 - \epsilon^{2780t}\,\{-1140 \sin 9900\,t + 3900 \cos 9900\,t\}$$

$e_3 = +3450 = \text{const.}$

$E_1 = 6000 - 4680\,\epsilon^{+435t} \sin 10{,}000\,t$

$E_2 = -6000 + 3220\,\epsilon^{+2780t} \sin 9900\,t$

$E_3 = 0$

Curve III. $r = 0$.

$i_1 = 142\,\epsilon^{+1420t} \sin 9900\,t$

$i_2 = -102\,\epsilon^{+1830t} \sin 9830\,t$

$i_3 = +62\,\epsilon^{+2600t} \sin 9650\,t$

$i_4 = -23\,\epsilon^{+4800t} \sin 8750\,t$

$i_5 = 0$

$$e_1 = 6000 + \epsilon^{+1420t}\,\{-2000 \sin 9900\,t + 14{,}000 \cos 9900\,t\}$$

$$e_2 = -6000 - \epsilon^{+1830t}\,\{-1870 \sin 9830\,t + 10{,}000 \cos 9830\,t\}$$

$$e_3 = +6000 + \epsilon^{2600t}\,\{-1660 \sin 9650\,t + 6000 \cos 9650\,t\}$$

$$e_4 = -6000 - \epsilon^{+4800t}\,\{-1120 \sin 8750\,t + 2000 \cos 8750\,t\}$$

$e_5 = +5200 = \text{const.}$

$E_1 = 6000 - 4000\,\epsilon^{+1420t} \sin 9900\,t$

$E_2 = -6000 + 3740\,\epsilon^{+1830t} \sin 9830\,t$

$E_3 = +6000 - 3270\,\epsilon^{+2600t} \sin 9650\,t$

$E_4 = -6000 + 2220\,\epsilon^{+4800t} \sin 8750\,t$

$E_5 = 0$

For the same values $C = 10^{-6}$; $L = 10^{-2}$ and $e_0 = 20{,}000$, Fig. 3 gives the discharge waves through an unsymmetrical gas circuit, varying from 8000 volts at zero current, to 1000 volts in the middle of the current wave, and then back to 4000 volts at zero current, and for the three values of constant ohmic resistance.

Curve I. $r = 50$ ohms.

$$\begin{aligned}
i_1 &= 131\,\epsilon^{-450t} \sin 9180\,t\\
i_2 &= 0\\
e_1 &= 5840 + \epsilon^{-450t} \{720 \sin 9180\,t\\
&\qquad + 14{,}160 \cos 9180\,t\}\\
e_2 &= 6330 = \text{constant}\\
E_1 &= 5840 - \epsilon^{-450t} \{5250 \sin 9180\,t\\
&\qquad - 2160 \cos 9180\,t\}\\
E_2 &= 0
\end{aligned}$$

Curve II. $r = 25$ ohms.

$$\begin{aligned}
i_1 &= 129\,\epsilon^{+545t} \sin 9300\,t\\
i_2 &= -\,29.3\,\epsilon^{+3450t} \sin 7900\,t\\
i_3 &= 0\\
e_1 &= 6180 + \epsilon^{+545t} \{-\,830 \sin 9300\,t\\
&\qquad + 13820 \cos 9300\,t\}\\
e_2 &= -\,7200 - \epsilon^{+3450t} \{-\,1340 \sin 7900\,t\\
&\qquad + 3120 \cos 7900\,t\}\\
e_3 &= +\,5100 = \text{const.}\\
E_1 &= 6180 - \epsilon^{+545t} \{4740 \sin 9300\,t\\
&\qquad + 1820 \cos 9300\,t\}\\
E_2 &= -\,7200 + \epsilon^{+3450t} \{3080 \sin 7900\,t\\
&\qquad - 790 \cos 7900\,t\}
\end{aligned}$$

Curve III. $r = 0$.

$$\begin{aligned}
i_1 &= 129\,\epsilon^{+1550t} \sin 9310\,t\\
i_2 &= -\,90.5\,\epsilon^{+2060} \sin 9070\,t\\
i_3 &= +\,55\,\epsilon^{+2880t} \sin 8500\,t\\
i_4 &= -\,20.5\,\epsilon^{+4500t} \sin 7320\,t\\
i_5 &= 0\\
e_1 &= 6500 + \epsilon^{+1550t} \{-\,5250 \sin 9310\,t\\
&\qquad + 13{,}500 \cos 9310\,t\}\\
e_2 &= -\,6700 - \epsilon^{+2060t} \{-\,5860 \sin 9070\,t\\
&\qquad + 9500 \cos 9070\,t\}\\
e_3 &= +\,7000 + \epsilon^{+2880t} \{-\,5110 \sin 8500\,t\\
&\qquad + 5700 \cos 8500\,t\}\\
e_4 &= -\,7500 - \epsilon^{+4500t} \{-\,3300 \sin 7320\,t\\
&\qquad + 2000 \cos 7320\,t\}\\
e_5 &= +\,6300 = \text{const.}\\
E_1 &= 6500 - \epsilon^{+1550t} \{4250 \sin 9310\,t\\
&\qquad - 1490 \cos 9310\,t\}\\
E_2 &= -\,6700 + \epsilon^{+2060t} \{4000 \sin 9070\,t\\
&\qquad - 1310 \cos 9070\,t\}\\
E_3 &= +\,7000 - \epsilon^{+2880t} \{3530 \sin 8500\,t\\
&\qquad - 1030 \cos 8500\,t\}\\
E_4 &= -\,7500 + \epsilon^{+4500t} \{2300 \sin 7320\,t\\
&\qquad - 500 \cos 7320\,t\}\\
E_5 &= 0.
\end{aligned}$$

As seen, the number of half waves of the discharge under these conditions of a high open-circuit voltage of the gas path, varies from one at the constant resistance of 50 ohms, to four with no ohmic resistance in circuit.

Fig. 4 shows the discharge curves, for the same constants $C = 10^{-6}$; $L = 10^{-2}$; $e_0 = 20{,}000$, for a low ohmic resistance, $r = 10$, and through an unsymmetrical gas path of lower voltage; from $E_0 = 3000$ volts at zero current, down to $E_m = 500$ volts for larger currents, and up again to $E_1 = 1000$ volts for zero current.

We have,

$$\begin{aligned}
i_1 &= 175\,\epsilon^{-67t} \sin 9720\,t\\
i_2 &= -\,131\,\epsilon^{+66t} \sin 9650\,t\\
i_3 &= +\,93.5\,\epsilon^{+278t} \sin 9510\,t\\
i_4 &= -\,61.6\,\epsilon^{+626t} \sin 9270\,t\\
i_5 &= +\,34.9\,\epsilon^{+1315t} \sin 8840\,t\\
i_6 &= -\,12.1\,\epsilon^{+3250t} \sin 7450\,t\\
i_7 &= 0\\
e_1 &= 1990 + \epsilon^{-67t} \{120 \sin 9720\,t\\
&\qquad + 18{,}010 \cos 9720\,t\}\\
e_2 &= -\,2010 - \epsilon^{+66t} \{-\,90 \sin 9650\,t\\
&\qquad + 13{,}610 \cos 9650\,t\}\\
e_3 &= +\,2050 + \epsilon^{+278t} \{-\,285 \sin 9510\,t\\
&\qquad + 9840 \cos 9510\,t\}\\
e_4 &= -\,2110 - \epsilon^{+626t} \{-\,450 \sin 9270\,t\\
&\qquad + 6620 \cos 9270\,t\}
\end{aligned}$$

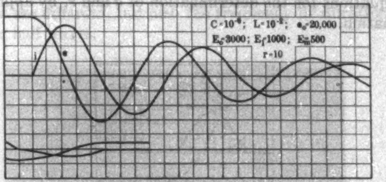

Fig. 4

$$\begin{aligned}
e_5 &= +\,2230 + \epsilon^{+1315t} \{-\,570 \sin 8840\,t\\
&\qquad + 3850 \cos 8840\,t\}\\
e_6 &= -\,2600 - \epsilon^{+3250t} \{-\,570 \sin 7450\,t\\
&\qquad + 1300 \cos 7450\,t\}\\
e_7 &= +\,2500 = \text{const.}\\
E_1 &= 1990 - \epsilon^{-67t} \{1510 \sin 9720\,t\\
&\qquad - 1010 \cos 9720\,t\}\\
E_2 &= -\,2010 + \epsilon^{+66t} \{1490 \sin 9650\,t\\
&\qquad - 990 \cos 9650\,t\}\\
E_3 &= +\,2050 - \epsilon^{+278t} \{1480 \sin 9510\,t\\
&\qquad - 950 \cos 9510\,t\}\\
E_4 &= -\,2110 + \epsilon^{+626t} \{1450 \sin 9270\,t\\
&\qquad - 895 \cos 9270\,t\}\\
E_5 &= +\,2230 - \epsilon^{+1315t} \{1380 \sin 8840\,t\\
&\qquad - 775 \cos 8840\,t\}\\
E_6 &= -\,2600 + \epsilon^{+3250t} \{1080 \sin 7450\,t\\
&\qquad - 410 \cos 7450\,t\}\\
E_7 &= 0.
\end{aligned}$$

It is interesting to note that in the successive half waves of discharge through a gas circuit, especially an unsymmetrical one, under these conditions the frequency decreases, that is, the wave length increases, by over 30 per cent between the last and the first half wave.

The exponential decrement steadily decreases, and thus changes from a decrement in the first half wave, to an increment of increasing amplitude in the successive half waves. If the ohmic resistance is small, the first half wave shows an increment.

D. Non-Sinoidal Discharge

As a further illustration there is shown, in Fig. 5, the first half wave of a discharge carried out to the third harmonic, through a symmetrical gas path and a constant ohmic resistance of such value as to make the decrement vanish, that is, to give $c = 0$; for the constants: $C = 10^{-6}$; $L = 10^{-2}$; $e_0 = 20{,}000$, and for the voltages of the gas path given as

$E_0 = 6000$ volts at zero current, at the beginning and the end of the half wave,

$E_m = 1000$ volts in the middle of the half wave, and

$E = 2000$ volts at 30 degrees after the beginning and before the end of the half wave.

The values E_0, E_m and E_2 substituted into equation (**6**) give five expressions for the determination of the five constants, $B_0, B_1, B_1', B_3, B_3'$. The four equations (**12**) express the values A_1, A_1', A_3, A_3' in the values of B, and, substituted into equations (**10**) and (**11**), give two equations for the determination of q and r, by approximation.

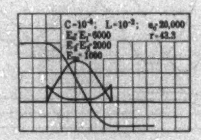

Fig. 5

This gives the value of constant ohmic resistance as $r = 43.3$ ohms, and the discharge equations,

$$
\begin{aligned}
i &= A_1 \sin q\,t + A_1' \cos q\,t + A_3 \sin 3\,q\,t \\
&\quad + A_3' \cos 3\,q\,t = 139 \sin 9946\,t + 3.6 \cos 9946\,t \\
&\quad + .2 \sin 29{,}838\,t - 3.6 \cos 29{,}838\,t \\
e &= B_0 \Sigma \left\{ (r\,A_k - k\,q\,L\,A_k' - B_k) \sin k\,q\,t \right. \\
&\quad \left. + (k\,q\,L\,A_k + r\,A_k') \cos k\,q\,t \right\} = 6000 \\
&\quad - 330 \sin 9946\,t + 14{,}100 \cos 9946\,t \\
&\quad + 80 \sin 29{,}838\,t - 100 \cos 29{,}838\,t \\
E &= B_0 - B_1 \sin q\,t - B_3 \sin 3\,q\,t = 6000 \\
&\quad - 6000 \sin 9946\,t - 1000 \sin 29{,}838\,t.
\end{aligned}
$$

Volt-Ampere Characteristics

Fig. 6 gives the volt-ampere characteristics (of the first half wave) of the preceding figures, that is, the potential drop of the gas circuit E, as ordinate, with the current as abscissas (in a fraction of its maximum value).

Line $C\,D$ (**2**) gives the E to i relation of the symmetrical gas circuit of Fig. 2.

Curve E-D-F (**3**) gives the unsymmetrical circuit of figure 3, with $E\,D$ for increasing, $D\,F$ for decreasing current.

Curve C (**5**) D gives the E to i characteristic of the discharge. Fig. 5, containing the third harmonic.

For comparison, $A\,B$ (r) is the volt-ampere characteristic of a constant ohmic resistance, and $C\,B$ (**1**) that of a gas path of constant voltage.

E. Asymmetrical or Unidirectional Conductor

The volt-ampere characteristics of gaseous conductors very often depend on the direction of the current flow, that is, the potential drop across the conductor, and its variations with the current are entirely different for the current flowing in one direction, from that of the current flowing in the reverse direction,—often very much lower. Such for instance is the case in the vacuum tube with one hot and one cold electrode, or a vacuum tube with one cold carbon electrode and one ionized mercury electrode. In this case the potential drop across the tube is very low and approximately constant if the incandescent or ionized electrode is negative, and the potential drop may be very high, especially at zero current in the beginning of the discharge, if the cold electrode is negative.

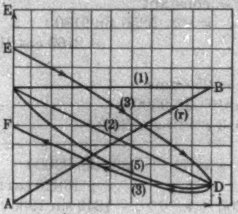

Fig. 6

Since the equations of the condenser discharge through a gas circuit have to be calculated for every half wave separately, the calculation of the condenser discharge through such a unidirectional or "rectifying" conductor is the same, the only difference being that for alternate half waves of discharge, different constants are used.

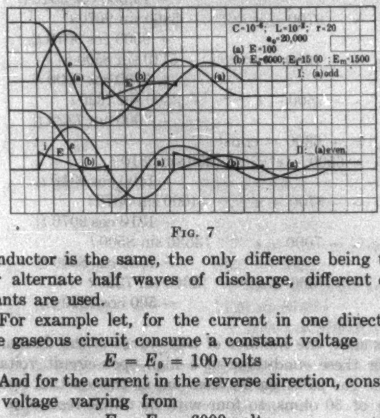

Fig. 7

For example let, for the current in one direction, the gaseous circuit consume a constant voltage

$$E = E_0 = 100 \text{ volts} \qquad \textbf{(a)}$$

And for the current in the reverse direction, consume a voltage varying from

$$E = E_0 = 6000 \text{ volts} \qquad \textbf{(b)}$$

at zero current, to

$$E = E_m = 1500 \text{ volts} \qquad \textbf{(b)}$$

in the middle of the discharge, and reaching again

$$E = E_1 = 1500 \text{ volts} \qquad \textbf{(b)}$$

for zero current at the end of the discharge.

Then the even half waves of the discharge are calculated with the one, and the odd half waves with the other set of constants, (*a*) or (*h*), as shown in Sections *B* or *C*.

Fig. 7 shows the two discharge curves, for

$$e_0 = 20{,}000; \quad C = 10^{-8}; \quad L = 10^{-2}; \quad r = 20$$

and, in Curve I for the first half wave being in the direction of the conduction of the gas path, (*a*), while in Curve II the first half wave of the current is in such direction that the gas circuit offers a high opposing voltage (*b*).

Fig. 8

The equations of the discharge then are:

Curve I. High Conductivity during Odd Half Waves.

$$i_1 = 200\, \epsilon^{-1000t} \sin 9950\, t$$

$$i_2 = -\, 93.3\, \epsilon^{+185t} \sin 8900\, t$$

$$i_3 = +\, 73\, \epsilon^{-1000t} \sin 9950\, t$$

$$i_4 = 0$$

$$e_1 = 100 + \epsilon^{-1000t} \{2000 \sin 9950\, t + 19{,}900 \cos 9950\, t\}$$

$$e_2 = -\, 3830 - \epsilon^{+185t} \{-\, 225 \sin 8900\, t + 10{,}470 \cos 8900\, t\}$$

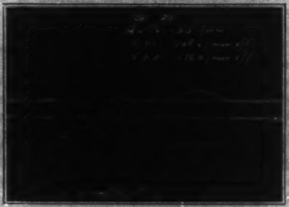

Fig. 9

$$e_3 = +\, 100 + \epsilon^{-1000t} \{730 \sin 9950\, t + 7270 \cos 9950\, t\}$$

$$e_4 = -\, 5160 = \text{const.}$$

$$E_1 = 100$$

$$E_2 = -\, 3830 + \epsilon^{+185t} \{2260 \sin 8900\, t - 2180 \cos 8900\, t\}$$

$$E_3 = +\, 100$$

$$E_4 = 0.$$

Curve II. High Conductivity during Even Half Waves.

$$i_1 = 151\, \epsilon^{-237t} \sin 9270\, t$$

$$i_2 = -\, 114\, \epsilon^{-1000t} \sin 9950\, t$$

$$i_3 = +\, 28\, \epsilon^{+2060t} \sin 7530\, t$$

$$i_4 = -\, 33.6\, \epsilon^{-1000t} \sin 9950\, t$$

$$i_5 = 0$$

$$e_1 = 3660 + \epsilon^{-237t} \{425 \sin 9270\, t - 16{,}340 \cos 9270\, t\}$$

$$e_2 = -\, 100 - \epsilon^{-1000t} \{1140 \sin 9950\, t + 11{,}350 \cos 9950\, t\}$$

$$e_3 = +\, 4650 + \epsilon^{+2060t} \{-\, 935 \sin 7530\, t + 3450 \cos 7530\, t\}$$

$$e_4 = -\, 100 - \epsilon^{-1000t} \{335 \sin 9950\, t + 3340 \cos 9950\, t\}$$

$$e_5 = +\, 2300 = \text{const.}$$

$$E_1 = 3660 - \epsilon^{-237t} \{2240 \sin 9270\, t - 16{,}340 \cos 9270\, t\}$$

$$E_2 = -\, 100$$

$$E_3 = 4650 - \epsilon^{+2060t} \{2070 \sin 7530\, t - 1350 \cos 7530\, t\}$$

$$E_4 = -\, 100$$

$$E_5 = 0.$$

It is interesting to note, that not only the amplitudes and the decrements of the odd and of the even half waves are different, but also the frequency or duration of the half waves.

Fig. 10

As the calculated curves given in the preceding section show a number of characteristics different from the usual oscillating discharge curves, a series of oscillograms was taken of such an inductive condenser discharge through a gas circuit. Three of these oscillograms are given in Figs. 8, 9 and 10.

The gas circuit consisted of a vacuum tube of 1 1/2 in. diameter and 36 in. length, with tungsten electrodes.

The inductance was measured as $L = 7.4$ h., the capacity 1.7 μf; the ohmic resistance of the circuit $r = 34.5$ ohms, and the initial voltage of the condenser discharge was $e_0 = 10{,}000$ volts.

These oscillograms very decidedly show the characteristics calculated in Figs. 2 and 4:

A discontinuity in the slope of the discharge current at the reversal.

The wave shape of the current, characteristic of a cumulative discharge, that is, decreasing more abruptly than increasing (the reverse of the usual damped discharge.)

The gradual increase of the wave length, that is, decrease of *q*.

These three characteristics becoming more pronounced towards the end of the oscillation.

The residual charge left in the condenser—in this case gradually leaking out through the oscillograph shunt.

The oscillograms give the discharge current, the voltage across the vacuum tubes, and a 60-cycle timing wave.

In Fig. 8, the air pressure in the vacuum tube was 5 mm. of mercury. The oscillation consisted of two half waves, of maximum currents $i = 6.25$ and 2.85 amperes, and wave length constants $q = 176$ and 164. The second half wave of voltage gives $E_0 = 4150$; $E_1 = 3080$; $E_m = 1530$.

In Fig. 9, the air pressure was 3.5 mm. of mercury. Three half waves occurred, with maximum currents $i = 6.7$; 3.17; $.88$ amperes, and wave length constants $q = 228$; 218; 203. The second wave gave $E_0 = 2830$; $E_1 = 2430$; $E_m = 1480$.

In Fig. 10, the air pressure was 0.01 mm. of mercury, and the voltage curves therefore are of materially different appearance. Five half waves occurred of the maximum currents $i = 8.2$; 5.42; 3.75; 2.53; 1.58 amperes, and the wave length constants $q = 250$; 242; 230; 215; 199. The second half wave gave $E_0 = 3030$; $E_1 = 2470$; $E_m = 530$.

Discussion

V. Karapetoff: I shall first consider the specific cases treated by the author, and then the general case, which he puts first.

The first two cases, A and B, correspondong to $E = 0$ and $E =$ constant; they do not require any special or new method of integration of the fundamental eq. (**4**), since the troublesome term, $d\,E/d\,t$, vanishes. Hence, these cases lead to familiar decremental sinusoidal expressions. The fact that in the second case the discharge stops after a finite number of alternations is very interesting, and it follows directly from the nature of the circuit.

In the case C the shape of the current wave is assumed *a priori*, so that no integration of the fundamental equation is necessary. This case seems somewhat arbitrary, in that a physical quantity, E, instead of being taken in the beginning as a certain function of i, according to experimental facts, is deduced theoretically from an assumed law of variation of current. Of course, the shape of the current in the oscillograms (Figs. 8 to 10) shows the reasonableness of such an assumption, but the mathematical results for q and c are so complicated as to minimize the importance of this case.

In the remainder of the paper the author also seems to treat cases in which eq. (**4**) is not integrated in its general form, and no use is made of the empirical relationships between E and i, quoted at the very beginning of the paper. On the contrary, these relationships are deduced theoretically (Fig. 6).

While such a treatment may be valuable as a first approach to the subject and while the theoretical curves have considerable similarity with the actual oscillograms, a somewhat different approach, more in accordance with the physical facts of the passage of electricity through gases, is also desirable. The very purpose of the "General Case" treated at the beginning of the paper should be to indicate the solution of the problem for a given empirical relationship between E and i, and yet the author does not seem to use this method at all in his special cases.

I therefore suggest the following alternative treatment of the general case: Since

$$d\,E/d\,t = (d\,E/d\,i)\,(d\,i/d\,t) \qquad \textbf{(a)}$$

eq. (4) may be written in the form

$$L\,\frac{d^2\,i}{d\,t^2} + (r + d\,E/d\,i)\,d\,i/d\,t + i/c = 0 \qquad \textbf{(b)}$$

or

$$\frac{d^2\,i}{dt^2} + \varphi\,(i)\,d\,i/d\,t + a\,i = 0 \qquad \textbf{(c)}$$

where $\varphi(i) = 1/L\,(r + d\,E/d\,i)$ **(d)**

and $a = 1/(L\,C)$ **(e)**

The quotient $d\,E/d\,i$ may be called the ionization slope of a gas. It is a negative quantity which characterizes the reduction in the resistance of the gas with the increase in current. For solid metals at a constant temperature this factor is a positive constant and represents the ordinary ohmic resistance. Thus, the expression in the parentheses of eq. (**d**) may be called the *generalized resistance* of the circuit, and is one of the data of the problem.

The advantages of eq. (**c**) over Dr. Steinmetz's eq. (**4**) are as follows: (1) Eq. (**c**) contains only one dependent variable, i, as a function of t. Eq. (**4**) has two dependent variables i and E. (2) In Eq. (**c**) the given gas is characterized by its permanent and general physical property, $d\,E/d\,i$; in eq. (**4**) it is characterized by a specific variable factor $d\,E/d\,t$, which applies only to a particular circuit. (3) Eq. (**4**) apparently requires a complicated solution with $(4\,n + 3)$ simultaneous equations for the determination of the integration constants. Eq. (**c**) can probably be solved by assuming a simple algebraic function for $\varphi\,(i)$, and using a method of approximations. In fact $\varphi\,(i)$ may be assumed to vary in steps, in which case for each step $\varphi\,(i)$ is a constant, and the usual solution, of the form of eq. (**15**), holds true. (4) Eq. (**c**) can be reduced to a differential equation of the first order by putting

$$d\,i/d\,t = p \qquad \textbf{(f)}$$

In this case $\dfrac{d^2\,i}{d\,t^2} = d\,p/d\,t = (d\,p/d\,i)\,(d\,i/d\,t)$

or

$$\frac{d^2\,i}{d\,t^2} = p\,(d\,p/d\,i) \qquad \textbf{(g)}$$

Eq. (**c**) becomes $p\;d\,p/d\,i + p\,\varphi\,(i) + a\,i = 0$ **(h)**

While I doubt if this equation can be integrated in the general form, certain plausible assumptions may possibly be made in regard to $\varphi\,(i)$ and p, to enable an approximate integration of this equation to be carried out, for practical purposes.

There are some minor statements in the paper which ought to be corrected. For example, the solution of a differential equation is called an integral equation; the latter term is used in modern mathematics in an entirely different sense. The quantities C and q are called "integration constants" which they are not, being functions of the given circuit constants. The equation (**7**) may be a particular solution only, and nothing is said of the complementary function, such as the solution of case A. Eq. (**4**) is supposed to have only two constants of integration, being an equation of the second order; the statement that it has $4\,n + 3$ such constants ought to be explained more in detail.

Charles P. Steinmetz: I was considerably interested in Professor Karapetoff's remarks, as I also tried to introduce the direct relation $d\,e/d\,i$ into the equations but found that the relations between e and i usually met in gaseous conduction—some of them being indicated in my paper—are such that the resulting differential equation cannot well be integrated. I therefore resorted to the method usual in such case, to represent the inconvenient relation by a Fourier series and use the first terms of this series. In other words, started from a special simple solution of the general equation and from this determined the conditions of the $e - i$ relation.

Speaking of the $2\,n + 3$ constants as "integration constants" is an obvious lapse; "indeterminate constants" was meant.

The dynamic characteristic of the general $e - i$ relation I have introduced by the asymmetry of the $e - i$ relation adopted. In the oscillograms given in the paper, the frequency is sufficiently high to give a strongly marked dynamic form of the characteristic—the frequency is seen by comparison with the 60-cycle timing wave shown in the oscillograms.

The Petersen Earth Coil

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***Review of the Subject.**—Accidental arcing grounds on transmission lines constitute the foremost problem to be solved in the transmission of electrical energy over great distances. There has come into use to a limited extent, arcing ground suppressors. This device consists in principle, of a switch in the station which is automatically closed in parallel with the accidental arc at any point out on the system. The parallel path through the switch shunts the current from the arc and thereby extinguishes the arc. This development is not yet completed.*

This paper gives the results of some experiments on an entirely different device for suppressing accidental grounds—a device that was first advocated by Prof. W. Petersen of Darmstadt, Germany. The essential part of this new apparatus is a suitable reactor connected between the neutral of the circuit and ground. This reactance is chosen of such a value as to neutralize the capacitance of the circuits when an accidental ground of one phase takes place. Under this accidental condition the reactor is electrically in parallel with the active capacitances and, by the well-known fundamental law, the only current that flows to the combination of the inductance and capacitance in parallel is the current necessary to supply the energy loss in the combination. The simplified equivalent conditions are shown in Fig. 4. This energy current can be made very small and it is this relatively small current that passes through the accidental arc to ground. If the ground is of the arcing type, the arc will, under favorable conditions be extinguished, as the energy flowing through the fault is only that necessary to supply the losses in the resonant circuit. If the losses are low, the energy flowing through the fault will be insufficient to support an arc and the voltage of the resonant system is gradually reduced to zero, while the voltage between the former faulty wire and ground gradually rises to normal value.

In a comparison of the various methods of grounding and their effects on the operation of a power system, the solid and the low-resistance grounds assume first and second place in the order of desirability. The distinction however, between these two is slight and choice will be determined by local conditions. Either the Petersen earth coil or the critical-resistance ground will assume third place in the order of desirability as the relative advantages and disadvantages of these two are about equal.

The advantages of the Petersen earth coil system are: first, the suppression of arcing grounds under favorable conditions; second, the reduction of insulator trouble; and third, small earth current when a fault occurs to ground.

The disadvantages are: first high potentials between line and ground due to series resonance; second, maintenance of a series of arcs under unfavorable conditions, that is, resonance and high loss, or large dissonance and either high or low loss; third, difficulty in obtaining selection of the faulty line by means of relay protection; fourth, reduced lightning protection due to the necessity of high settings on arresters; and fifth, increased system insulation due to the shifting of the neutral with abnormals or transients.

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  Series Resonant System. (190 w.)
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  Effect on the Insulation of Systems. (175 w.)
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V. Conclusions. (330 w.)

THE use of an inductance coil connected between the neutral of a power system and ground is advocated in an article by Prof. W. Petersen of Darmstadt, Germany, in the *Electrotechnische Zeitschrift*, January 2nd and 9th, 1919. This inductance is resonated at the fundamental system frequency with the capacity reactance of the power system to ground. It is claimed that when one wire becomes grounded the current flowing through the fault is of insufficient value to support an arc.

Additional information relative to the operation and limiting features of the earth coil has resulted from investigations and tests made in this country and a comparison made between this and other methods of grounding.

I. THEORY

The earth coil is applicable to single-phase and polyphase systems upon which a neutral may be established. For the sake of simplicity, however, the single-phase system will be considered first.

A single-phase transmission system is represented schematically in Fig. 1, involving a generator, G, a transformer, T, a capacity between wires 1 and 2, $C_{1\text{-}2}$, capacities between wire 1 and ground, and wire 2 and ground, C_1 and C_2 respectively, and an earth coil $E\,C$. A fault on wire 2 to ground short-circuits the condensers C_2 and the system may then be represented as shown in Fig. 2.

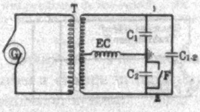

FIG. 1—APPLICATION OF AN EARTH COIL ($E\,C$) TO A SINGLE-PHASE CIRCUIT

Closing the switch F is equivalent to an accidental ground on wire 2 and actually short-circuits its capacitance.

Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

This diagram (Fig. 2) shows that the charging current for the line capacity C_{1-2} flows through the wires 1 and 2 as heretofore, but the charging current for the capacity C_1 flows through the earth coil *E C*, fault, and wire 1. The exciting current for the earth coil *E C* flows through wire 2, fault, and earth coil *E C*, forming with the capacity C_1 a parallel resonant circuit adjusted for resonance at fundamental power frequency. In practise, the currents through the earth coil and the capacity C_1 to ground are quite large but the two currents being almost in opposition as shown in Fig. 3, the resultant current, which is the current through the fault, is comparatively small, and is determined by the values of energy losses in the resonant system.

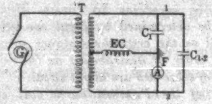

FIG. 2—SIMPLIFICATION OF FIG 1 WHEN WIRE 2 IS GROUNDED

The voltage on the capacitance between wires 1 and 2 remains constant but the voltage between wire 1 and ground has risen from half to full line-to-line voltage.

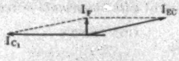

FIG. 3—CURRENT IN THE EARTH COIL (*E C*), CURRENT IN THE CAPACITANCE WIRE 1, AND THE RESULTANT CURRENT OF THE TWO (I_F)

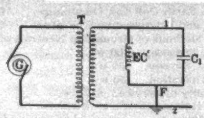

FIG. 4—SIMPLIFIED DIAGRAM OF FIG 2

The conditions of resonance of a reactor and condenser in parallel are shown more clearly in Fig. 4 in which the earth coil is replaced by an equivalent reactor, taking the same current and connected across the lines.

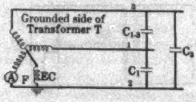

FIG. 5—APPLICATION OF THE EARTH COIL (*E C*) TO A THREE-PHASE CIRCUIT, WITH WIRE 2 GROUNDED

A three-phase star-connected system with earth coil is shown in Fig. 5. The operation of this system on the occurrence of a fault to ground is similar to the single phase system shown in Fig. 4 but in this case the earth coil is to be resonated with the sum of the currents through the capacities C_1 and C_3.

The earth coil may be tuned with the line capacities to ground under actual operating conditions by inserting an ammeter as shown in Fig. 2 and with one phase wire grounded adjusting the reactance of the coil for minimum current as shown in Fig. 6.

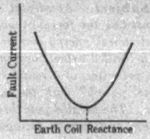

FIG. 6

The lowest part of the curve of current occurs at the value of reactance which gives resonance with the capacitance in parallel.

II. OPERATION

Effects of Resonance and Energy Loss. The most favorable conditions for the proper functioning of the earth coil, that is, the suppression for arcing grounds are perfect resonance and low energy losses in the resonant system. Under these conditions, the voltage across the fault, which is the difference between the supply voltage and the voltage of the resonant system, builds up gradually to the normal voltage to ground. When the current through the fault is interrupted, due to there being insufficient current to support an arc, the two voltages have magnitude and phase relations shown in Fig. 7. The voltage of the resonant system is then gradually reduced to zero by the dissipation of the energy losses and the voltage between the former faulty wire and the ground rises gradually to normal value.

The chief advantages of the Petersen earth coil system are due to the two characteristics, of small fault current, and the gradual rise to normal voltage on the lines after an arc has been extinguished. The earth coil avoids trouble from arcing grounds because it prevents the cumulative action of successive arcs and thus precludes the building up of high voltages, tending to cause serious disturbances.

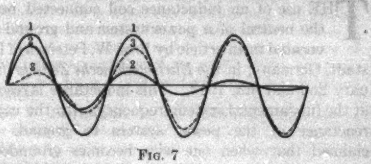

FIG. 7

1. Supply voltage.
2. Resonant voltage.
3. Voltage across the fault.

When the current through the fault is interrupted the voltage across the fault gradually rises and reaches normal value after a few cycles. (See the dotted curve.)

With perfect resonance, but high loss, the operation is as described above, except that the fault current is very much larger and may be of sufficient magnitude to maintain an arc, thus preventing a realization of the advantages of the earth coil.

Effects of Dissonance and Energy Loss. The effect of dissonance with either high or low loss is to cause the resonant system to have a natural frequency other than that of the supply, consequently the voltage across the fault may rise to a value slightly less than twice the star voltage in a period of a few cycles, as shown in Fig. 8. This voltage may be even larger than that which occasioned the fault and, as a result, a series of arcs may be maintained. System oscillations producing a succession of arcs may become cumulative in their effect and produce excessive voltages. The maintenance of such a succession of arcs, causes the transmission line as a whole to vibrate up and down in voltage and may lead to serious trouble.

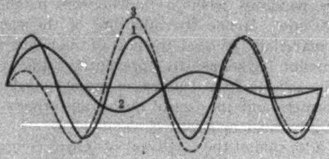

FIG 8—CONDITION OF DISSONANCE

1. Supply voltage.
2. Resonant voltage.
3. Voltage across the fault.

The voltage across the fault (dotted wave) is shown as rising above normal voltage in the second cycle after the arc ceases in the fault.

Both dissonance and energy loss increases the current through the fault and on this account an arc may be maintained. If the arc is maintained the transmission wire or insulation will probably be damaged to such an extent as to put the line out of commission effectively.

Voltage Between Sound Wires and Ground. When the equivalent of a non-arcing ground occurs on one wire, the voltage between the sound wires and ground will rise from Y voltage to line voltage above ground. But when there is a "make and break" through the accidental arc the transient voltage may rise to slightly less than twice line voltage. This high voltage is the result of a redistribution of energy in the resonant system at the instant the fault occurs.

Laboratory experiments made on an artificial line indicated that when a fault occurs, the sound wires will under extreme conditions, rise to 250 per cent or more of normal voltage. With the set-up of apparatus shown in Fig. 9 the application of a fault at the switch y produces the high voltages measured by the spark gap at the sphere gap x. In this respect, the earth coil system operates similarly to a *free neutral system*.

Series Resonant System. The system may also be considered as a series resonant system as shown in Fig. 1 in which current flows through the earth coil, $E\,C$, divides equally in the transformer T, and flows through the two line wires and through their respective capacities C_1 and C_2 to ground. Any voltage induced in series with the series resonant system will produce a current limited only by the losses of the system. The voltage which may appear between the neutral of the system and ground is determined by the impedance of the earth coil and the current flowing through it.

Voltage may be induced in the series resonant circuit by some other transmission line, by lightning discharges, by mutual induction, by unsymmetrical impedance under load, unequal capacities from line to ground, or such abnormal conditions as a single-phase short circuit or an open circuit on one wire. The induced voltage may be only a small percentage of the star voltage, but if the resistance of the system is low, and if resonance occurs, the voltage between one wire and ground may be many times the star value.

For this reason then, if the earth coil is used, special attention should be given to the transmission system to have it well transposed and balanced.

Maintenance of Resonance. The condition necessary for the most successful operation of the Petersen earth coil, that is, resonance and low energy loss, is difficult to obtain and maintain on a network composed of a variable number of feeders operating in parallel. For such cases adjustable reactors are required. Either a main earth coil may be provided with taps, so that the inductance may be adjusted for each change in line capacity, or an individual earth coil may be associated with each feeder, these coils being cut in or out with the feeder. Such complication, requiring a grounded connection on every feeder, appears to be very undesirable, and such installations are contrary to usual American practise.

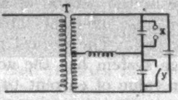

FIG. 9—CONNECTIONS OF AN ARTIFICIAL LINE TESTED IN THE LABORATORY

When a fault was produced at the switch y the voltage across the sphere gap x rose to two and a half times the normal value.

Lightning Protection. The installation of the earth coil necessitates a change in lightning arrester settings for the transmission system. With the grounded neutral system, the lightning arresters are set so as not to discharge for star voltage under wet weather conditions. With the earth coil in service, the protection must either be reduced by setting the arrester higher than line voltage or cutting the arrester out of service when a transmission wire becomes grounded. Neither of these alternatives is desirable. On systems where lightning disturbances are infrequent, the operation of the earth coil, requiring an increase in the setting of the arrester, may not be very detrimental, but in other regions the change in the lightning arrester setting would be very undesirable. If the earth coil were capable of satisfactory performance for various conditions, its operation would tend to relieve the arrester from interrupting the power arc which follows a lightning discharge.

The introduction of any impedance between the neutral point of a system and ground permits the *neutral to rise to a voltage above ground* during abnormal conditions. Hence the installation of the earth coil would impose greater voltage stresses on the transmission system under abnormal conditions, including lightning disturbances, than would be the case with a solidly grounded neutral.

Relay Protection. The installation of the earth coil in the neutral of a transmission network protected by any modern relay system prevents the automatic isolation of a grounded feeder due to the small differences in magnitudes and phase relations of the resultant currents flowing during the abnormal condition from those flowing under mormal conditions. Devices which give satisfactory indications showing the particular phase grounded are obtainable, but considerable difficulty will be experienced in determining immediately the particular feeder that is accidentally grounded.

An impracticable method of locating the faulty feeder is by an increase in current brought about either by the introduction of sufficient dissonance or by the increase of energy loss to such a value that the fault current will be of sufficient magnitude to operate the relays selectively. Under these two conditions the fault current may support an arc and the principal advantage of the earth coil installation will be lost.

As an alternative suggestion of a solution of the problem, it should be noted that the installation of a critical resistance at the neutral of a relatively small power system will also offer the same possibilities as a Petersen earth coil. The critical resistance at the neutral of a large system has the advantage of permitting sufficient value of current to obtain selective relay operation.

If the fault persists for an appreciable length of time, another method of overcoming the disadvantage of the earth coil is the installation of a relay in series with the earth coil which causes a switch in shunt with the earth coil to close and thereby solidly grounds the neutral of the system. When the earth coil is shunted by the switch, sufficient current for selective relay operation is permitted to flow. This is really a combination of two systems, initially an earth coil system, changing over to a solidly grounded neutral system and, therefore, it has some of the advantages and disadvantages of both. With this arrangement, it is evident that, if an insulator flashes over and the arc persists, the system just described would punish the insulator more than would be the case if a solidly grounded neutral were employed. On the other hand, if the earth coil system interrupts the arc following an insulator flashover, it is evident that the particular insulator would not be punished as much. However the insulators on the other phases would be subjected to higher voltages with the use of the earth coil than would be the case with solidly grounded neutral.

Effect on the Insulation of Systems. The Petersen earth coil system cannot be applied to transmission systems having transformers with graded insulation, due to the fact that when one line becomes grounded, the other lines rise to line potential above ground; nor to systems in which auto-transformers are used, due to the excessive voltages it would impress on low-voltage windings when a fault occurs in the high-tension side. Hence the adoption of the earth coil would materially increase the cost of the higher voltage transmission systems by preventing the possible economy arising from the use of graded insulation on transformers and the use of auto-transformers with a solidly grounded neutral.

The adoption of the earth coil system as compared to a grounded neutral system, would increase the voltage stresses which would be imposed upon transmission line insulators, on cable insulation, and on switching equipment. As a result, either the cost of line insulators and switching equipment would be increased or the factor of safety in insulation would be materially reduced.

III. OPERATING TESTS

Tests were made upon a 26,400-volt, three-phase, 60-cycle network of five lines totalling 59.8 miles, to obtain information relative to the operation of the Petersen earth coil and to collect data indicating the suitability of such an installation for the suppression of arcing grounds.

The charging currents of the systems were measured with various combination of lines as follows:

Lines in Service	Amperes Charging Current
H-112, *V*-126, *L*-142, *G*-111, *B*-132 (All Lines)....	11.2
H-112, *V*-126, *L*-142, .. *B*-132..................	10.5
H-112, *V*-126, .. *G*-111, *B*-132..................	10.6
H-112, *V*-126, *L*-142, *G*-111, ...	5.9
.. *V*-126, *L*-142, *G*-111, *B*-132..................	10.0
H-112, .. *L*-142, *G*-111, *B*-132..................	10.0

The Earth Coil of Variable Inductance. Approximately a 1450-ohm reactance, rated at about 160 kv-a. was required for installation at the neutral of the system to resonate with the capacitance. This value was made up by connecting the high-tension side of a 300-kv-a. transformer (ratio of 13,200/2,400 volts) between the neutral of an 11,500-kv-a. transmission transformer (ratio of 13,200/26,400 volts) and ground. Two 100-kv-a. distribution transformers (ratio of 2400/240-480 volts) were connected to the low-tension side of the 300-kv-a. transformers, and on the low tension side of the two 100-kv-a. transformers a 250-ampere, 5 per cent feeder reactance (1.525 ohm) was connected. Adjustment of the correct reactance value was obtained both by changing the ratio of transformation and by tapping off only such portion of the reactance coil as needed.

Tuning the Earth Coil and Dissonance. The earth coil was adjusted to resonate at 10.5 amperes, which is the charging current for the electrostatic capacity of four feeders of the network, consisting of the second group of lines in the table above, viz.: *H*-112, *V*-126, *L*-142, and *B*-132. Line *G*-111 was out of service. Leaving the earth coil reactance constant and reconnecting *G*-111 (charging current 11.2 amperes) a condition of +7 per cent dissonance[1] was established. Next, disconnecting *B*-132 a condition of − 44 per cent dissonance was established. In addition to providing convenient operating conditions, these combinations of feeders provided a wide range for tests. Incidentally the weather was hot and dry at the time the earth coil was tuned. There had been no rain for several days and therefore the line leakage was small.

FIG. 10—FILM 13

Reactance of the Earth coil is at resonant value. Phase No. 1 is grounded at the instant shown in the oscillogram of sudden change of currents and voltage. The three records are as follows: The upper record (right scale) measured the current in the fault. This current is shown as a wide zero line until the ground is made on phase 1 when the deflection suddenly rises to a peak value of about 7 amperes.

The middle record (middle scale) measure the current in the earth coil. This current has a peak value of nearly 1.5 amperes (the small thick lined wave) even under normal insulation of the three phases. This current is due to unbalanced conditions of the three phases. When phase 1 is grounded the current in the earth coil rises to a steady state value with an average peak of about 16 amperes.

The lower record (left scale) measures the voltage of a non-grounded phase; that is, phase 3 to ground. When phase 1 is grounded, phase 3 rises from *y* voltage to delta voltage.

The Petersen coil was adjusted for 60-cycle resonance under service conditions by measuring the current through a ground fault applied to No. 1 phase of Line *H*-112 and measuring the current through the coil. A number of progressive changes were made in order that the point of minimum current through the fault indicating resonance, might be determined. The unneutralized or residual current under this condition was 2.7 amperes with 11.9 amperes through the earth coil.

The total energy loss in the system under dry weather conditions, determined by the decrement method, was about 30 kw. of which about 12 kw. occurred in the earth coil. The energy (not voltage) loss in the earth coil might be reduced somewhat for a permanent installation, by making up a specially wound coil, but the loss in the earth coil being the minor fact, the total loss could not be greatly reduced. The effect of wet weather conditions will be to increase the energy losses and this factor can not be controlled.

Tests—Grounding and Ungrounding One Phase. In addition to other tests, oscillograms were taken to show the ability of the earth coil to suppress arcing grounds and to obtain data on the operation of the coil during the transient state.

A fault was placed on phase No. 1 of feeder *H*-112 at the station end, with various combinations of transmission lines in service. Tests were made with resonance and with + 7 per cent and − 44 per cent dissonance. In each of these dissonance tests the shortening of the gap by closing a disconnecting switch caused a steady arc discharge as the blade approached the jaw of the switch. On opening the switch there was no evidence of an arc. These results indicated

FIG. 11—FILM 15

Reactance of earth coil is at resonant value. The ground on phase 1 is removed at the instant shown in the oscillogram of sudden change of currents and voltage. The three records are as follows:

The upper record (right scale) measures the current in the earth coil. When the switch representing the fault is opened, the current drops from the continuous value it previously had to zero (shown by the wide horizontal line of the upper record).

The middle record (middle scale) measures the current in the earth coil. When the switch representing the fault is opened the current in the earth coil does not drop immediately to zero value as in the case of the current in the fault. The current in the earth coil first rises a little and reduces gradually through three successive cycles to the small value of unbalanced current that is characteristic of the system.

The lower record (left scale) measures the voltage between ground and a non-grounded phase. After the ground is removed from phase 1 this voltage gradually through three cycles reduces to less than *y* value and recovers in two cycles to *y* value.

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[1] In this article the use of ± *a* per cent dissonance indicates that the charging current was *a* per cent greater or less than that required for resonance.

that, for dry weather condition, considerable variation in the number of lines connected in service was permissible without destroying the effectiveness of the earth coil to suppress the arc.

The oscillograms, for example, film 13, indicated that there was a certain amount of dissymmetry in the three phases of the transmission system which caused current to flow in the circuit composed of the transmission lines and the capacity to ground, returning to the lines through the earth coil and the step-up transformers. The magnitude of this circulating current was determined by the change in magnitude of load current, but was, however, quite small—about one ampere.

The voltages of the different phases to earth changed almost instantly with the application or removal of the fault. This result was to be expected as the change of voltages takes place as rapidly as the line capacity charges or discharges.

At resonance, and during the steady state condition, the current through the fault (film 15) appeared quite peaked, having a maximum value of 4.5 amperes. The corresponding maximum value of current through the earth coil was 17 amperes. On closing the fault, the current built up through the earth coil in from 3 to 4 cycles. On opening the fault, the current through the fault dropped to zero immediately and the voltage between phase 3 and ground became stable in 4 to 5 cycles. There was a noticeable overcharge during the transient which occurred on opening the fault as shown by the voltage, phase 3 to ground, in films 15 and 16.

During the transient which occurred when the fault was closed with a condition of +7 per cent dissonance, the current through the fault reached a maximum value of 18 amperes, and the current through the earth coil, a maximum of 70 amperes. The transient lasted for about 4 cycles, during which the current through the fault reduced to a steady state maximum value of 4.5 amperes and that through the earth coil to a maximum value of 17 amperes.

On closing the fault with a condition of −44 per cent dissonance, the current through the fault reached a maximum value of about 45 amperes and through the earth coil a maximum of 100 amperes. After a transient lasting from 12 to 15 cycles, the current reduced to a steady state values of 7 amperes maximum through the fault and 16 amperes maximum through the earth coil.

These tests showed that for the steady state the current through the fault and the current through the earth coil approached the same steady value, and that the transient current on opening the fault lasted the same number of cycles. However, on making the fault, the character of the transient current depended upon the particular instant at which the switch was closed. During the transient conditions there appeared to be an even harmonic in the earth coil current. This effect of an even harmonic was probably due to the unidirectional flow of energy, to re-establish balanced conditions, which caused the transformer to become saturated. Hence during the transient condition the peaking of the current wave during one half of the cycle and the flattening of the wave during the other half of the cycle were to be expected from the particular conditions that existed for this test. In addition, a path for the return of negative current from a local street railway was provided by the fault, the current flowing through the fault, the transmission wire, the transformer, and the earth coil to ground. This flow of direct current would also tend to saturate the transformer and produce even harmonics.

Fig. 12—Film 16

Reactance of Earth coil adjusted to resonant value. As before, the ground on phase 1 is removed at the instant shown in the oscillogram of sudden change in the voltages. This oscillogram shows three voltages (no currents). The records are as follows:

The upper record (right scale) is the voltage of phase 1 to ground. This voltage is shown as a wide zero line until the switch representing the fault is opened when it rises in four successive cycles to a value slightly greater than its normal *y* value oscillates to less than normal and then returns to normal.

The middle record (middle scale) is the voltage across the earth coil, that is to say from neutral to ground. This voltage drops gradually in four successive cycles to the small constant value which is characteristic of the unbalanced system.

The lower record is too dim to reproduce. It is the voltage of the non-grounded phase 3 to ground. In four successive cycles it gradually reduced from delta value to *y* value.

Tests were also made to determine the possibility of maintaining a continuous series of arcs by moving the fault disconnecting switch back and forth within arcing distance. The test was made with +7 per cent dissonance, and with wet weather condition, the air being very moist and the transmission system having been thoroughly soaked by a heavy rain a few hours before the tests.

Under the above conditions a power arc was maintained. The arc was approximately two inches long and several inches broad, and was of a yellow color. The arc was noisy and appeared to the eye to be fluctuating, that is, forming a continual series of arcs. The effect of the arc was to cause the blade and jaw of the disconnecting switch to become slightly pitted at various points.

An oscillogram of this arcing condition, film 25, while rather difficult to follow, brought out a few points of interest. The maximum value of the current through the fault was from 80 to 100 amperes; the maximum value of the current through the earth coil was probably in excess of 70 amperes. The magnitude of the current through the earth coil indicated that the maximum value of voltage between neutral and ground was about 1.3 times normal.

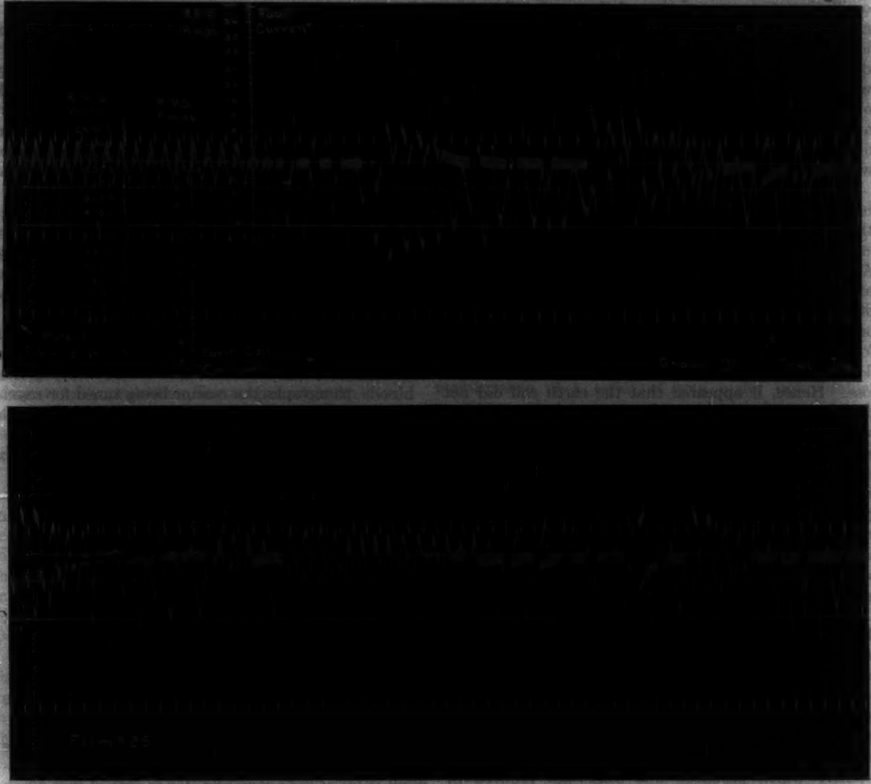


Fig. 13—Film 25

Earth coil not tuned to exact resonance. Dissonance plus 7 per cent. After a severe rain storm an arcing ground was established on phase 1. Again the upper record is the current at the fault, the middle record is the current in the earth coil, and the lower record the voltage to ground of a non-grounded phase.

The oscillogram starts with the condition of metallic ground showing an alternating current wave to ground. This wave is ragged with harmonics (probably 3rd, 5th and 7th). When the switch representing the fault is opened to an arcing position both the current in the arc to ground and the current in the earth coil made many sudden large changes in value. There is great irregularity due to the various instants in the cycle that the arc is extinguished and again established. The current in the arcing ground shows now and then a gradual adjustment toward zero. This was described in the text.

The current in the earth coil shows dangerously high values which carry the deflecteous far off the edge of the film. The most severe current rushes are too dim on the photograph to reproduce (one of these large deflecteous is scratched in).

There appeared to be a certain regularity as to the period at which the arc was interrupted. This average value was from 1.8 to 2 cycles. To explain this uniformity of the re-establishment of the arc, the theory of beats caused by the fundamental frequency and the natural frequency of the oscillating system, has been put forth. On this basis the estimated dissonance was found to be from 6 to 7 per cent. When the fault was applied the two systems vibrated at the supply frequency and the phase relation between these two systems was such as to cause negligible voltage across the disconnecting switch. When the fault was removed the two systems drifted apart causing the voltage across the disconnecting switch to reach a maximum value in about two cycles. The voltage caused by the oscillating system consisting of the earth coil and line capacities was gradually reduced to zero by the energy losses in this circuit. Hence, the most probable condition for the re-establishment of the arc occurred within a number of cycles corresponding to one half of the difference between the resonant frequency and the supply frequency. The resonant frequency obtained from the above considerations checked well with the increased line capacity.

These tests showed a peculiar wave shape of the residual and of earth-coil currents. This current of the earth coil was shown as a heavy wide line, which curved at a relatively slow rate to the zero value. Apparently this curve was due to the snapping out of the arc at an instant when energy was left in either of two forms, namely, a direct charge stored in the system, or electromagnetic energy stored in the current transformer. This stored energy caused a current to flow until the energy was entirely converted into I^2R loss. Hence, it appeared that the earth coil did not dissipate direct charges entirely, and therefore, did not operate in a way to remove completely the cause of arcing grounds. Reference to film 25 shows that the maximum current through the earth coil, and therefore the maximum voltage between the neutral and ground was preceded by a series of arcs occurring at uniform intervals, indicating that the earth coil system under certain conditions permits system oscillations which are cumulative and produce voltages between neutral and ground which may reach excessive values.

In connection with film 25, it should be noted that with the exception of the weather, the conditions with only 7 per cent dissonance were favorable to the operation of the earth coil. There was no doubt but that the chances for obtaining an arcing ground would have been much greater if line *B*-132 had been cut out of service. The effect of the + 7 per cent dissonance was to increase the effective condenser capacity which probably was somewhat reduced in effect by leakage resistance. During the tests of the arcing condition, the lightning arresters were in service and discharged frequently.

IV. COMPARISON OF METHODS OF GROUNDING NEUTRALS OF SYSTEMS

Five methods of grounding the neutral are considered and an order of preference given for each from the view points of voltage stresses, current stresses, relay operation, continuity of service and cost. This arrangement is designed to give a clear conception of the status of the earth coil with respect to other methods of grounding and a comprehensive view of the relative advantages of the different methods.

It should be understood that a general comparison of this kind cannot be of a definite and precise character. There are many factors which must be considered and sharp distinctions cannot be made in the analysis. All that is attempted here is to give a general idea based upon a broad classification of the important items that require consideration.

For the purpose of this article, the five methods of grounding the neutral are defined as follows:

v. *Dead Ground.* The neutral connected directly to the grounded earth plate without the installation of reistance or reactance coils.

w. *Low Resistance Ground.* A ground connection to the neutral having a resistor of the order of two to four ohms permanently installed between the neutral and ground plate.

x. *Critical Resistance Ground.* A ground connection arranged as in the preceding paragraph *w*, but of the critical value of resistance necessary to damp out the natural oscillation of the system. In general, this will be a high resistance compared to two to four ohms.

y. *Petersen Earth Coil.* A ground connection to the neutral through a reactor, which takes the place of the resistor of the two previous paragraphs the reactor being tuned for resonance at fundamental system frequency with the capacity of the system to ground.

z. *Infinite Resistance from Neutral to Ground.* This is the ungrounded or free neutral system.

Effect on	Order of Preference				
	1	2	3	4	5
A—Voltage Stresses					
(a) At normal frequency	v	w	x, y, z		
(b) Due to arcing grounds	x, y	v, w	z		
(c) Due to lightning	v	w, x	y, z		
B—Current Stress	z	x, y	w	v	
C—Relay Operation	v	w	x, y, z		
D—Continuity of Service	v	w	x	y	z
E—Cost					
(a) Insulation of power system	v	w	x, y	z	
(b) Grounding devices	z	v	x	w	y

A—Voltage Stresses.

(*a*) *At normal frequency* the dead ground limits the voltage stress which may occur to a constant maximum value of approximately 50 per cent of that which may occur in any other form of ground connection. With the low resistance ground, the voltage stress across transformers may be something less than line voltage.

(*b*) *Due to arcing grounds.* From a technical standpoint the critical resistance and the earth coil under the favorable conditions assumed in the table of comparison, seem to be the most desirable for the suppression of arcing grounds. Under unfavorable conditions the earth coil does not deserve first choice because of the possibility of producing excessive voltages due to the cumulative effects of a series of arcs. However, experience shows that most any system of grounding is found to be sufficient to reduce the troubles arising from arcing grounds. From a practical operating point of view, many companies prefer to ground the neutral solidly or dead and isolate the feeder on which the ground occurs.

(c) *Due to lightning.* Three factors enter into the question of lightning protection. The installation of any impedance between the neutral of the system and ground tends to place additional voltage stresses on transformers and other apparatus. From this standpoint a dead grounded system is to be preferred and the earth coil and ungrounded system are the least to be desired. A second factor is the effect of the installation of a critical resistance which tends to damp out the natural oscillations. A third factor is the adjustment of lightning arresters. With the dead grounded system, the arrester may be adjusted approximately to star potential, whereas with the other methods, it is necessary to adjust for practically line potential.

B—Current Stresses.

The current stresses on apparatus due to currents flowing to ground through a fault are obviously zero with the ungrounded system and a maximum with the dead ground. With a grounding system permitting adequate relay protection, line to ground faults should not develop into line to line faults, hence the use of an impedance in the neutral would reduce the duty on breakers.

C—Relay Operation.

The reliability of relay operation is dependent upon the value and uniformity of the characteristics utilized to select the faulty lines. The dead ground is therefore to be preferred, as the variations in the resistance of the fault may limit the current flow to such values as to give incorrect relay operation if a resistance or other current limiting device is installed.

D—Continuity of Service.

In any power system the essentials necessary for the provision of continuous service are: first, the prevention or reduction of disturbances which may result in failure of apparatus, lines or equipment, and second, the isolation of apparatus, lines or equipment in the event of failure.

Since the means of prevention or reduction of disturbances on power systems has not developed to the extent that relay protection has been developed, a majority of the power companies prefer to rely on the latter method. The dead ground is, therefore, to be preferred which permits the utilization of full current values for selective relay operation. From a purely operating standpoint, however, some difficulty is experienced in holding synchronous machines in step after a fault has been cleared on a dead grounded system. Consequently a low resistance is generally installed in the neutral. The introduction of any impedance in the neutral connection tends to limit the distortion of the voltage triangle in case of a ground on one wire and thus to increase the probability of synchronous machines staying in step.

E—Cost.

(a) *Insulation.* Theoretically, there will be a difference in the cost of insulating a power system in favor of the dead ground. Advantage has not been taken of this fact, except for high-voltage systems; most power companies preferring to employ the additional factor of safety.

(b) *Grounding Devices.* Of course the ungrounded system is the cheapest in this respect and the dead ground without the installation of limiting devices is the next preference, the installation of the earth coil being most undesirable, particularly if it is necessary to employ reactors associated with each feeder.

V. CONCLUSIONS

The advantages of the Petersen earth coil system are: First, the elimination of arcing grounds under favorable conditions; second, the reduction of insulator trouble; and third, small earth current when a fault occurs to ground.

The disadvantages are: First, high potentials between line and ground due to series resonance; second, maintenance of a series of arcs under unfavorable conditions, that is, resonance and high loss, or large dissonance and either high or low loss; third, difficulty in obtaining selection of the faulty line by means of relay protection; fourth, reduced lightning protection due to the necessity of high settings on arresters; and fifth, increased system insulation due to the shifting of the neutral with abnormals or transients.

An analysis of the table giving an order of preference, results in the following arrangement of the different methods of grounding from the viewpoint of desirability: First, dead ground; second, low-resistance ground; and third, critical-resistance ground or the Petersen coil. The distinction however between dead ground and low-resistance ground is very slight and choice will be determined by local conditions. Either of these is generally preferable to the critical resistance or Petersen earth coil. An installation of an earth coil on a free neutral system would probably result in a reduction in interruptions to service. An installation of an earth coil on a dead grounded system would probably show no improvement in service and under most circumstances would introduce complications. In this connection, it is pointed out that reduction in interruptions are not significant, if made on the basis of a change from free neutral to earth coil, but merely prove that a grounded system is better than an ungrounded neutral system.

Numerous technical difficulties with the earth coil have been pointed out and it is interesting to find that some of these points, such as high potential due to series resonance, have given rise to serious interruptions in some European installations.

Discussion

W. W. Lewis: In the paper by Messrs. Conwell and Evans it is interesting to note that the only part which gives actual data, that is, Section 3, shows that the Pertersen coil functioned satisfactorily in the manner that it was intended to function, that is, as an arc suppressor. The conditions under which the arc was made were not those usually existing in practise. In the tests an arc was made between switch blades with a comparatively small separation, say a couple of inches or so. Under these conditions the residual current even though small may be enough to maintain an arc. In practise the arc is usually over an insulator with 10 or 12 in. arcing distance and considerable current is required to maintain such an arc even without the neutral reactor.

In the author's comparison of methods of grounding neutrals of systems (page 147) they give for continuity of service first order of performance to the grounded neutral system and fourth to the Petersen coil system. This seems to be a curious inversion of order. That system which is deliberately intended to cause a short circuit and an interruption in case of an arc-over is placed first, and that system which puts out the arc without interruption is placed next to last.

It seems to the speaker that the authors have not made a good comparison between the system with Petersen coil and the isolated and grounded neutral systems. The Petersen coil system really stands between the two. As far as voltage stresses are concerned it is an improvement over the isolated neutral system but not as good as the grounded neutral system. As far as current stresses are concerned it is an improvement over the grounded neutral system, and probably also over the isolated neutral sytem in which an arc-over usually results in a short circuit. It is applicable to moderate voltage systems in which the charging current is low, hence the ohmic reactance of the neutral coil high, so that the reactance of the transmission line itself has practically no effect on the neutral current. Under this condition it is comparatively easy to obtain a balance and the residual arc current may be kept at a minimum no matter at what point on the line the arc takes place. However, on high-voltage sytems or very long low-voltage systems, the charging current is large, hence the ohmic reactance of the neutral coil low. The reactance of the transmission line on the other hand is high so that it is difficult to maintain a balance for arcs at different points on the line and there may be enough residual current to maintain the arc. In no event, however, can the voltage strains be as severe as on an isolated neutral system. In view of these considerations the field of the reactor at the present time would seem to be limited to moderate voltage, moderate length systems.

Some tests were made by the speaker on a 100-mile, 44,000-volt power system in the South equipped with a neutral grounding reactor. The tests were made to approximate operating conditions as nearly as possible. The line was energized and from one conductor to ground was placed a circuit consisting of an oil circuit breaker an insulator or horn gap, a current transformer and ground. Across the insulator was placed a one-ampere fuse. The oil circuit breakers was closed allowing the current to flow to ground, blowing the fuse and causing an arc. The setting of the reactor could be changed by means of taps. All told about 50 arc-overs were made with different settings of the reactor, different lengths of line, pin-type and suspension-type insulators and horn gaps, with the line carrying load and with the line unloaded. In all these tests the coil acted satisfactorily as an arc suppressor even with, in the terms of the authors, as much as plus 60 per cent and minus 20 per cent dissonance. There was in the majority of cases a conspicuous absence of measurable overvoltages such as feared by the authors.

C. L. Fortescue: The theory of the Petersen earth coil is presented in the simplest form when considered in terms of symmetrical coordinates. Thus, for example, at the point at which ground occurs, the system has impressed on it: (1) The normal polyphase voltages which may be resolved into positive and negative phase sequence symmetrical components, and which since their sum at any instant is always zero, can produce no ground current, and, therefore, will have no effect on the choke coil connecting the neutral to ground.

(2) The zero phase sequence voltage tends to cause a flow of current through ground. These currents are of zero phase sequence, and have been termed by telephone engineers residual currents. Under the condition of ground, therefore, we shall have quite obviously a circuit to this zero phase sequence component consisting of the joint capacity of all the wires to ground and the Petersen coil in multiple.

Let us now consider the action of such a system when a ground takes place. Since the impedance of all the conductors in multiple is quite low, there will be an initial rush of charging current. During the period of adjustment, this charging current will set up high surge potentials in apparatus connected across the lines. After the steady condition is attained, the system consisting of the zero phase sequence line capacity and the Petersen coil will oscillate naturally at fundamental frequency.

We have at the instant of zero current, the point of contact at ground potential, and the system oscillating at its natural period, at a zero phase sequence potential equal to the voltage from line to neutral. Therefore there will be no potential between the point at which the ground initiated, and earth and the arc will not be re-established after the first cycle.

Through the dissipation of energy in the system the line will gradually resume its nominal zero phase sequence potential, which, if there be no dissymmetry in the system, will be zero.

So far the system appears to be ideal, but let us examine it still further:

(a) The ground current is not the contact current, but will be very large, especially in large cable systems, where the capacity of all the conductors to ground has a large value. The ground current is the capacity current when all the conductors are charged to a potential above ground equal to the Y voltage. The duration of this condition depends upon the closeness of the resonance, thus if there were no losses in the system during resonance, the time would be prolonged indefinitely. The interference or residual currents, are, therefore, not small and they extend through the system for its complete length.

(b) Unbalanced impedance in the lines, will cause under load conditions a zero phase sequence e. m. f. in the system to which the Petersen earth coil and the line capacity form a resonant system. If the losses are low, there will be nothing to prevent a high potential being induced in the system. If a short circuit takes place between lines in which there is dissymmetry, the potential to which the system may be raised is very high.

Breakdown of lines, of transformer, generators and motors will all produce high potential rises, and a fault, which, with a dead grounded neutral would be confined to a narrow scope, may be spread to other parts of the system.

(c) In a large interconnected system, we would have the undesirable condition that a ground on one feeder would raise the potential of the whole system. This might result in dangerous conditions for the users of power where their circuits are not grounded.

(d) The transient condition at the installation of the short circuit may cause severe surges in connected inductive apparatus.

(e) From the point of view of electrical apparatus in general, the system is undesirable. It is introducing an uneconomical system to take the place of a standard of power transmission and distribution, which has been established and is the result of a great deal of experience and careful thought.

It should be borne in mind that in the long run, the system that is most favorable to the power producer and user will also work out best for the telephone system.

The dead grounded neutral system has become standard. This condition has not been reached by haphazard means, but it is the result of a long history of bitter experience with isolated systems.

The speaker was among the first to recognize the advantages of the dead grounded neutral, and has lived to see the opinions of transmission engineers come around to this point of view as the result of actual experience in the field. We must guard against permitting the alleged advantages, in a narrow field, of such a device as this one under discussion taking hold of our imaginations. If it has applications in a certain field, let us define this field as closely as necessary to prevent misapplications of it, which may lead to serious trouble in the future.

In considering the relations between the power and telephone interests, we should guard against concessions to the latter which will hold back the development of the power resources of this country. One of the essential requirements for furthering the rapid development of power is a stable system of transmission and distribution. This can be obtained only with a dead grounded neutral system. The general recognition of this system as the standard will lead to standardization in line materials, insulation, transformers, etc., so as to produce better performance at the least cost.

In considering the relative merits of the two cases in the controversy, we should keep in mind the ultimate investment, and the system which will make this the minimum will be best suited to our needs.

H. M. Trueblood: The authors speak of resonanting the earth coil with the sum of the currents through two of the line capacities to ground. One ordinarily thinks of resonance as a condition obtaining between two reactances, rather than between a reactance and a current. It would possibly lead to confusion, however, if the statement were taken to mean that the earth coil inductance is to be resonated with the sum of the capacities to ground of the two non-grounded phases. The earth coil inductance should be resonant with the sum of the *three* capacities to ground, that is, if with solidly grounded neutral, the three Y-connected legs of the transformer bank be energized with three equal fundamental frequency voltages, all in phase, the quadrature component of the neutral current should be equal in magnitude to the same component of the current taken by the reactor when energized by one of the same three voltages. This current component will, however, also be equal to the sum of the currents taken by *two* line capacities with the third phase grounded when the system with neutral isolated is energized three phase at the same star voltages as before, provided the voltages and capacities to ground are balanced. The reason is of course that in the latter case the reduction in total capacity to ground is exactly counter-balanced by the higher voltages to which the two capacities are subjected, combined with the effect due to their phase displacement (60 deg.). If the neutral is grounded through a correctly tuned reactor, instead of isolated, the quadrature components of current (referred to the star voltage of the grounded phase) through the line capacities and through the reactor annul each other at the fault, so that, as stated in the paper, the minimum reading of an ammeter carrying the fault current indicates correctness of tuning. An ammeter located as shown in Fig. 5 would carry a charging current for wire-to-wire capacity as well as the fault current.

This equality of the quadrature current taken by the reactor at star voltage to the sum of the currents taken by the capacity to ground of two phases, with the third grounded, is what constitutes the "parallel resonance" of the system. As is explained in the paper, it is this condition, which exists only when one phase is grounded, that operates to extinguish the arc to ground. The "series resonance" condition is equally fundamental to the operation of the reactor. As is perhaps not quite clearly explained in the paper, it is this condition which becomes operative to prevent the restriking of the arc, after the condition of parallel resonance has brought about extinction of the arc, and has thereby ceased to exist. It is because of this "series resonance" that the current taken by the total direct capacity to ground at star voltage is equal to the quadrature reactor current at the same voltage, as previously pointed out. The transition from the "parallel" to the "series" resonance condition takes place when the arc goes out, and is accompanied by no appreciable transient due to fundamental frequency, if extinction occurs when the fundamental frequency current passes through zero. At this instant, the fundamental frequency charges and currents in the system have the proper values for both types of oscillation, except perhaps for slight deviations due to system losses.

In their discussion of dissonance the authors might be understood as stating that the phase which had been grounded might within a few cycles be subjected to a voltage slightly less than twice the star value, with dissonance and with either high or low loss. Over-voltage due to dissonance will be more pronounced with low than with high loss. The resultant voltage shown in Fig. 8 can hardly be described as slightly less than twice normal. It would seem to be rather less than 1.4 normal, and would evidently be greater if the damping were smaller.

In referring to the trouble which may be produced by voltage vibration on a transmission line, the authors presumably do not mean that the effects would be worse than with isolated neutral under similar circumstances.

The experimental result showing that with a single-phase set-up a voltage to ground 250 per cent of normal, *i. e.*, 125 per cent of line voltage is obtained on the sound wire, checks quite well with some theoretical calculations I have made regarding this matter. It would be interesting to know whether similar tests with free neutral were made, and if so, what results were obtained. I have been unable to discover any theoretical reason for expecting greater over-voltage with the Petersen than with the free neutral system from transient effects rising from the redistribution of energy referred to in the paper. With the Petersen system, the principal transient term is nearly the same as with the free neutral system, and there is an additional non-oscillating term due to dissipation in the circuit consisting of coil and grounded transformer leg. This, however, is insignificant compared to the other, so far as the voltage from a sound phase to ground is concerned.

The authors state that with "a 'make and break' through the accidental arc, the transient voltage may rise to slightly less than twice line voltage." It is not quite clear just what is intended here, but if a single "make and break" is referred to it seems unlikely that the highest voltage of a sound phase to ground would exceed 125 to 150 per cent of line voltage.

An oscillating system responds with large effect only to impressed forces of approximately its natural period. It is therefore not easy to see why lightning is given as a possible source of resonant effect in the "series resonant" circuit. As to inductive effects due the action of currents belonging to the system itself, which I presume are what is referred to in mentioning "mutual induction," "unsymmetrical impedance under load" etc., I think these will be relatively small so long as the currents are confined to the line conductors and are not of excessive magnitudes, *i. e.*, are not short-circuit currents. When the currents are confined to line conductors the inductive effects of interest in this connection arise from differences in the mutual inductances between line wires, and the distribution of current among the latter is thus not a factor of great importance. In some cases I have calculated, the effect from balanced and symmetrical currents of about full-load magnitude is nearly the same as from a single-phase current of the same magnitude per wire. Neither was large. There is a further reason why the effects of such induction in the series resonant circuit is lessened. It is that the induction does not take place directly in this circuit. The induced voltage is distributed linearly along the circuit. So is the capacity of the resonant circuit. The two are therefore not directly in series. If the system consists of a single line, the effect of this factor alone is to reduce the current in the resonant circuit by 50 per cent of what would be if the induction occurred directly in series. Furthermore, this current can be reduced to an insignificant amount by transpositions. The effects of short circuits cannot, of course, be entirely avoided by transpositions. In a single line system of considerable kv-a. capacity, it would seem that the neutral might be raised to a considerable fraction of star voltage above ground by a single-phase short circuit, under circumstances favorable to the production of such an effect. In a multi-line radial system or in an interconnected network, the effect of a single-phase short circuit would be much smaller.

Unbalance of line capacities probably produces the most important effect of any non-accidental sources of induction. To keep their effect small it is necessary that the ratio of the vector sum of the three admittances to ground to their arithmetical sum be small compared to the ratio of the resistance of the coil to its reactance. This should usually be obtainable with only a modest amount of transposing.

Induction from the voltages of neighboring power circuits would not be in the series circuit except in the rather rare case of a practically complete parallel to all lines of the system on which the coil is installed. It should therefore usually be of relatively small effect, except possibly when the neighboring system is in trouble.

It is difficult to verify the statement that "the induced voltage may be only a small percentage of the star voltage, but if the resistance of the system is small, and if resonance occurs, the voltage between one wire and ground may be many times the star value." Assume a ratio of 1/10 for the coil resistance to its reactance and assume also that the "small percentage" of the star voltage is not more than 10. The voltage thereby produced between wires and ground would be about one times star voltage. If it were exactly in phase with one of the line voltages to ground, the highest resultant line voltage to ground would be about twice star voltage. By reducing the coil resistance-reactance ratio and increasing the "small percentage", this might be brought up to 3 times star voltage, but it would be hard to get it higher. Seven to eight per cent of star voltage in the series resonant circuit would be a liberal estimate for the voltage due to capacity unbalance, even if the line is not transposed at all.

The authors describe an interesting series of tests and advance explanations of a number of effects that were observed. They have not, however, collected into a separate series of statements the conclusions which they draw from this experimental work, and it is difficult to decide just what inferences one is expected to make. The discussion of film 25 on page 147, and also in the fine print under Fig. 13, seems to indicate that the authors believe that excessive or dangerous voltages between neutral and ground must have occurred, because of the large instantaneous values of reactor current. On page 146, however, they state that "the magnitude of the current through the earth coil indicated that the maximum value of voltage between neutral and ground was about 1.3 times normal." If this means 1.3 times star voltage, it seems hardly larger than might be expected even without an arcing ground. I would like to ask whether the authors do not suppose that the excessive currents observed in the fault and in the earth coil, in the arcing test and also in some of the other tests, are due to saturation in the transformers which were used in the connection from neutral to ground. Apparently the 13.2 kv. transformer was worked at some 20 per cent above normal voltage, with one phase grounded, even under steady state conditions, and of course the exciting current would be considerably larger than normal with this excess above normal voltage. The figure given for reactor current in the test for adjustment of resonance appears to indicate some effect due to saturation.

It seems to me that the drawing of conclusions of general applicability from these tests is very considerably complicated by the presence of a factor so difficult to evaluate as over-saturation of iron. Some of the other peculiar effects shown in film 25 may be connected with it. Certainly it must be agreed that this film is rather difficult to follow. For instance, in the author's discussion of the non-oscillatory shape occasionally present in the trace of one of the currents on this film, they are apparently talking about the coil current, yet the oscillogram looks as though it were the fault current which has this characteristic.

On page 145 the authors speak of a "noticeable overcharge during the transient which occurred on opening the fault as shown by the voltage, phase 3 to ground, in films 15 and 16." The trace of this voltage is too dim to be seen on film 16 and is not present on film 15, unless the film is incorrectly labelled. Presumably the effect to which they refer is that which appears in the phase voltages on the two films, however. It is due, I believe, to inexactness of tuning. It may be seen that the frequency of the coil voltage in film 16 and the coil current in film 15 slows down as soon as the free oscillation begins. The ratio of the frequency of this oscillation to that of the fundamental appears to be about 8:9. If the tuning were exact, the reactor voltage in film 16 should be in the same or the opposite phase (depending on the polarity of vibrator connections) to the voltage on the phase from which the fault has been removed. The two appear to coincide at about the third maximum after the beginning of the free oscillation, and this apparently produces the overvoltage on phase one.

Livingston P. Ferris: I have given the Petersen earth coil some consideration from a different point of view from that of the authors and have had an opportunity to see several of the European installations. These I will describe very briefly and then outline some facts showing the effect of the device on induction in neighboring communication circuits.

Rome Municipal Line—22 miles—Twin Circuits. Two 30,000-volt, 3-phase 42-cycle, 7500-kv-a., star-connected generators are connected direct to line. The transformers at the Rome end are delta-delta. The system was first operated isolated. Trouble developed with the insulation of generators at times of line faults. A Petersen coil was installed in the Castelle Modame Station in January 1920. A visit to this station was made in July 1920. The chief of the station was questioned at length and some test records were examined. He was convinced that the action of the Petersen coil had been beneficial. This is not a typical installation, but if its testimony can be believed, it is against the presence of excessive over-voltages as otherwise no benefit would have resulted. This installation is decribed by Lombardi in *L'Ellectrotechnica*, August and September, 1920.

Alta Italia-Line—65 Miles: 42-47 kv., 3 phase, 21,000-kv-a. Two star-connected auto transformers make slight changes in voltage between generating station and receiving station in Turin. A Petersen coil is installed between neutral of the star-delta receiving transformers and ground. It had been in service 1½ years at the time I interviewed Ing. Palestrino and saw the coil in October 1920. Previous to installation of coil, the neutral was isolated. Ing. Palestrino considered that the coil had been beneficial in reducing interruptions. A new coil of larger capacity was then under construction to replace the original. It was proposed to apply a Petersen coil to a 75-kv. circuit. The Alta Italia installation is described by Palestrion in *L'Ellectrotechnica* for July 5, 1920.

A number of other installations exist in Italy where the system is being given serious study by a committee of the I. E. A., headed by Prof. Lombardi who has published a number of articles on its theory and application. It will be of interest to know that Petersen, according to Lombardi, does not advocate exact resonance, but rather that the coil should have 10 to 15 per cent less reactance than the line. This was mentioned in connection with a discussion of unsymmetrical capacities and I suggested to Lombardi that the difficulty arising from such dissymmetry could be easily overcome by transposing the circuit. To illustrate how practical this is, the following figures are presented, based on experiments on a 36-mile power circuit of vertical configuration (one of the most unbalanced types). Residual voltage, fundamental frequency, isolated neutral. untransposed line, 6.9 per cent of voltages between wires. After two transpositions were installed on poles nearest third points, the residual voltage was too small to measure, but certainly less than 0.6 per cent. The residual voltage in this case is a measure of the capacity unbalance.

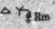
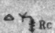
Swiss installation: One of the most extensive and interesting applications of the Petersen system is in Switzerland. Here it is applied with a number of coils to a very high-voltage cable and transmission line network. The coils in this case have air cores whereas in all other cases they had iron cores. Here apparently the purpose is to reduce damage to cable at times of fault by limiting fault current to the relatively small loss current rather than full charging current to ground in case of isolated systems or short-circuit current in case of grounded system. Of course, with a cable one can scarcely expect a fault to heal like some flashovers on a line. A high-voltage cable network would be about the last place to apply a Petersen coil if there were danger of serious transient over-voltages. I refrain from speaking more specifically of this Swiss case as the engineers responsible have not yet published their views. I have reason to expect they will do so in the near future.

No information which I have been able to obtain on any European installation would warrant the rather vaguely stated final conclusion of the paper. It would seem proper that the authors should submit more specific evidence in its support.

Now as to the bearing of this device on inductive interference problems, a matter ignored by Petersen and all other Europeans

COMPARISON OF DIFFERENT METHODS OF GROUNDING THE NEUTRAL

From Standpoint of Residual* Voltages and Currents

Method of grounding neutral	Under abnormal conditions ground on one phase		Under Normal Conditions				
			Fundamental		Harmonics not of triple series		Harmonics of triple series
	Residual voltage	Residual current	Residual voltage	Residual current	Residual voltage	Residual current	Residual voltage and current
1 Peterson Coil 	$\sqrt{3}\,E$	Max. $\frac{E}{\sqrt{3}}\, l\,\omega\, C\,g$ at Coil Zero at other end of line.	May be large if capacities are unbalanced to ground. Can be made unimportant if line is transposed.	May be large if capacities are unbalanced to ground. Can be made unimportant if line is transposed.	Practically same as (2) 104%— 5th 100%—29th	Practically same as (2)	15%—3 rd 1/2%—27th
2 Infinite Impedance (Isolated) 	$\sqrt{3}\,E$	Max. $\frac{E}{\sqrt{3}}\, l'\,\omega\, C\,g$ at fault, between 50% and 100% of max. for (1). Zero at ends of line.	Larger than (3) or (4) but smaller than (1) $3\,E\,\frac{C\,r}{C\,g}$	Zero	Depends on unbalance of line capacities. Can be made small as desired by transpositions. Relative magnitude 100%.	Much smaller than (3) Zero at ends of line.	Zero
3 Zero Impedance (Solid Ground) 	$\frac{E}{\sqrt{3}}$	Short circuit current, same everywhere between fault and neutral. Large compared with (1) or (2).	Zero except for dissymetry in transformer voltages.	Smaller than (1) when due to unbalanced capacities. With multiple grounds may be large.	Zero except for dissymetry in transformer voltages and slight effect of capacity unbalance.	Depends on unbalance of line capacities and dissymmetry in transformer voltages.	Depends on transformer design rating excitation and line constants. Relative magnitude 100%.
4 Moderate Resistance  Less than *Rc* generally larger than faulty phase impedance	$\sqrt{3}\,E$ Max. value for low impedance fault.	$\frac{E}{\sqrt{3}\,R\,m}$ Small compared with (3).	Much smaller than (1) (2) or (5).	Same as (3) or slightly smaller.	Approximates (3) Much smaller than (1), (2) or (5).	Approximates (3) Larger than (1), (2) or (5).	Smaller than (3) much larger than (1). More effective at higher frequencies.
5 Critical Resistance 	$\sqrt{3}\,E$	$\frac{E}{\sqrt{3}\,R\,c}$ Usually smaller than (4).	Larger than (3) or (4) but usually smaller than (1) or (2).	Smaller than (4).	Slightly larger than (3) or (4). Smaller than (2).	Lies between (3) and (2) depending on extent of system.	Smaller than (4). Larger than (1) at least at higher frequencies.

* —Vector sum of voltages to ground or vector sum of line currents.
E —Normal voltage from wire to wire.
$C\,g$—Total direct capacity to ground per mile of 3 wires in parallel.
l —Length of line in miles.
l' —Maximum length of line on one side of fault.
$C\,r$—Residual capacity = combination of 3 direct capacities in 120° relation.

and not mentioned by Messrs. Conwell and Evans. To appreciate this it is necessary to make comparisons with other systems of grounding or not grounding power circuits. To facilitate such, the foregoing table is presented. It compares the residual voltages and currents for different methods of grounding the neutral of a power circuit and for different conditions, normal and abnormal. As the balanced currents and voltages are inherently the same, irrespective of the condition of the neutral, they do not enter into our comparison of different systems. The possible inductive effects of corresponding factors of the several systems are, of course, directly proportional to the magnitudes of those factors in their respective systems.

From the above table, it will be noted that the Petersen system will, under conditions of a ground, produce inductive effects from voltage unbalances of the same order of magnitude as those produced by an isolated system, and that these are approximately three times as great as would be produced by a system with neutral solidly grounded. Electric induction from this cause will affect neighboring open-wire telephone lines, but will have no effect on underground telephone circuits, and relatively little effect on telephone circuits in aerial cables, if the sheath is grounded. The magnetic induction from the residual current will obviously be very much greater in the case of the grounded neutral system than in the case of a system grounded through the Petersen coil or isolated. The magnetic induction will furthermore affect underground as well as open-wire circuits. Theoretical studies and experience combine to indicate that the effects of induced voltages in case of a fault to ground, considering both electric and magnetic components, are more severe with the solidly grounded neutral than with the isolated system except perhaps in case of long exposures involving very high-voltage power circuits. This is largely because of the greater transfer of energy by magnetic induction with the grounded neutral. From a theoretical study of the Petersen coil, it would be expected that the effects under abnormal conditions would be quite similar to those produced by isolated systems, except that the tendency to prevent the formation of arcing grounds would constitute a considerable advantage for the Petersen system, as the results of an arcing ground are proportionately as undesirable from the standpoint of neighboring telephone circuits as from the standpoint of the power system.

Under normal load conditions, the principal effect of the Petersen coil is practically to suppress the inductive effect of such triple harmonics as may arise from the transformers in a grounded neutral system, thus making it approximate the isolated system as regards the absence of induction from triple-harmonic residuals. So far as harmonic residuals not of the triple series are concerned, these remain practically the same with the Petersen coil as with the isolated neutral, and are capable of reduction by the same method, namely power circuit transpositions.

Detailed comparisons of inductive effects from residuals under abnormal and normal conditions and including systems employing a resistance in the neutral connection, may be based on the table. It should be remembered that under normal load conditions, the inductive effects of the balanced components must also be considered. Under abnormal conditions, the inductive effects of the balanced components are generally masked by the much larger effect of the abnormal residuals.

Under abnormal conditions, the magnitude and phase of the residual current or unbalanced current to ground at all points in an isolated network or one grounded through a Petersen coil, may be very closely determined by considering all three phases in multiple and replacing the fault by a single-phase generator connected between the 3 multipled phases and ground, whose voltage is equal in magnitude but opposite in phase to the normal voltage of the grounded conductor and whose internal impedance is equal to that of the fault. If we are interested in the actual currents in the several phases, these may be obtained by combining the unbalanced currents with the normal load and charging currents. This method of analysis is very helpful on occasions and leads to quick results.

In discussing the effect of the Petersen coil on the selective action of relays, the authors point out a real difficulty but may we not hope that if the advantages of the Petersen coil are sufficient in other respects this difficulty may be overcome. The authors, themselves, suggests a means of avoiding this difficulty if not of overcoming it, by shunting the Petersen coil with an automatic switch which may either solidly ground the neutral or cut in any desired amount of resistance. The authors claim that such a combination system would punish an insulator more than would be the case if a solidly grounded neutral were employed. It is not apparent that there would be much difference or that it is of importance. I would suggest in this connection, that if instead of reverting to a solidly grounded neutral, a moderate resistance were cut in by the switch, not only the insulator in question would be spared from punishment but, also, neighboring communication circuits. For all those cases which the Petersen coil may clear without interruption, both the power circuit and neighboring communication circuits are the gainers. It remains to be determined by experience whether cases of the latter kind will be a sufficiently large proportion of the total to warrant the use of a combination system.

I wish to make it clear that I do not regard the Petersen coil as a panacea for all inductive difficulties but merely that it is of sufficient importance to warrant a comprehensive, and preferably cooperative, study from all points of view, to bring into light all the pertinent facts by which it must be judged. As yet, we have no experimental data bearing particularly upon inductive interference but, of course, data as to its effect on the power circuit give us a good guide as to what we may expect since the two are intimately related. Primarily and fundamentally, the device must satisfy power circuit requirements. If this is done, we should then, in particular cases where inductive interference is involved, give due weight to its advantages or disadvantages from this and other standpoints along with those of all other systems in arriving at a decision as to which should be used. I think this is a basis upon which we may all agree.

F. C. Hanker: Most of the comparisons made today have been made with the free neutral system. Such a basis of comparison seems rather surprising when one considers the actual practise in power systems, the growth and inter-connection of systems. A number of years ago it was felt that the size of a transmission system or the extent of a net work would be limited on account of the effect of arcing grounds, a phenomenon incident to the operation of a free neutral system. Since that time, the tendency has been more and more toward the grounded neutral system and for that reason I believe that the basis of comparison of power systems would be a grounded neutral system.

The Petersen coil has certain advantages if it could be worked in with existing power systems and if it did not in any way limit the expansion of power service. With respect to continuity of service, which is really the criterion of best service, which would be of advantage to the power company and customer, our experience has shown that the grounded neutral system has had a far better record than was the case in the days of the free neutral system. This means that we must recognize the possibility of arc ground disturbances when the characteristics of a free neutral system are approached. It also follows that we must devise and develop protective devices that will take care of such disturbances, and not put a handicap on power systems and limit their development. It has been stated a number of times that there are possibilities of protector breakdown and fire hazard and other difficulties as a result of magnetic induction. Experience has not always borne out these possibilities. When power systems are compared the basis should be on what promises to be the best service conditions to the customer, taking into account future growth and interconnection of systems.

The study of the earth coil indicates that the application is limited. High-voltage transmission lines or extensive cable systems are not favorable for the application of the earth coil because of the high charging currents involved. The earth coil is not suitable for application on systems where graded insulation or auto-transformers are employed, because the neutral point cannot be solidly grounded. Complicated networks are not favorable for the application of the earth coil due to the difficulty of securing isolation of faulty feeders. The most suitable conditions for the application of the earth coil are on moderate voltage systems of rather limited extent, particularly those where duplicate transmission lines do not exist. It appears, therefore, that the earth coil is not suitable for general application on power systems.

H. S. Warren (communicated after adjournment): The "Petersen earth coil," so-called, has an important effect from the inductive interference standpoint. One of the most difficult problems in inductive interference-prevention is that of avoiding the severe surges of high voltage induced in a telephone circuit when a fault develops on a paralleling power circuit. Such a situation will be clear from the following diagram. (Fig. 1).

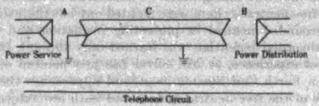


FIG. 1

The transformer at *A* supplying power to the transmission circuit is shown with the neutral of its high-tension winding solidly grounded. Under conditions as shown, with normal load and the circuit balanced, no current of fundamental frequency will flow through the neutral connection. When, however, the insulation fails, as at *C*, grounding one phase wire through the fault either solidly or through an intermittent arc, the voltage of that phase is suddenly short-circuited through the grounded phase wire, fault, and earth back to the neutral, thereby causing a large current through the loop consisting of the faulty phase and earth. By electromagnetic induction this large current through the grounded loops sets up a large voltage along the wires of the paralleling telephone circuit. These suddenly induced voltages produce various harmful effects, the most serious of which in recent experience is that of acoustic shock to telephone operators.

Now as to the bearing of the Petersen earth coil on this matter. If the Petersen coil were used in the neutral ground connection, the current at such times of fault, through the fault and the earth loop, would be relatively small and thereby the severe electromagnetically induced surges avoided. It should perhaps be added that the foregoing has in view more particularly transmission lines of lower voltage, as compared with the highest voltage lines now in operation.

If the resistance were inserted in the neutral ground connection the short-circuit current through the fault would be, of course, less than with a solidly grounded neutral. By making the resistance high enough the induced voltage can be made as small as desired. The method of high resistance in the neutral ground connection is therefore an alternative to the Petersen reactor as a possible solution of this inductive interference problem.

If the use of the Petersen earth coil proves feasible from the power standpoint, it will be of considerable benefit from the standpoint of telephone service where parallels exist. To a certain extent the interests of the two services are alike for if the Petersen coil were objectionable from the power standpoint by reason of causing large overvoltages which break down the power line insulation, it would for the same reason be objectionable from the standpoint of surges induced in neighboring telephone circuits.

It is fundamental, of course, that the Petersen coil cannot be used under conditions where it is incompatible with the service requirements of the power company. It would be fruitless to employ a preventive of interference to telephone service which would introduce interference to power service. However, the possibilities of adapting the Petersen earth coil to practical conditions encountered in this country have not yet been fully studied and it is obvious from the remarks of several speakers that some power engineers are more optimistic regarding the Petersen coil than the authors of the paper. If there is a lack of full understanding as to certain aspects of the functioning of this device and the effects and reactions which it produces under different conditions, the engineers interested should investigate these questions.

A. E. Silver: From the results brought out in Messrs. Conwell and Evans' paper, from the discussion offered and information from other sources, it is clear that the application and performance of the device is dependent upon several power systems characteristics, all subject to variation through a wide range for different systems and, for any specific system, each subject to variation, in a degree that cannot be predetermined, of such factors as total length of circuits interconnected, quality of line insulation changing with dust deposits and atmospheric conditions, and others that must be taken into account in adjusting the earth coil. The coil can function ideally, if at all, for only one assumed set of these conditions. Furthermore, the disadvantages that have been pointed out must be kept clearly in mind, especially the danger to apparatus insulation from rises in voltage to ground. Having learned, after much theorizing through the hard and costly school of experience, the value of the dead grounded neutral in protecting insulation and draining off abnormal potentials from our power systems, we must not compromise this essential safeguard without sufficient and well weighed reasons.

It would appear that no rule can, at this time, be set down of general practicability and benefit from this device. In the main any system under consideration must be taken up for individual study and determination as to successful performance, safety to apparatus and economy. Theoretical study alone, no matter how great, is inadequate and this determination cannot be made with assurance until sufficiently extensive experience with installations under service conditions has been gained to give a good knowledge of the range of conditions under which the device will function successfully without sacrificing safety of apparatus or imposing other undue disadvantages. It may be found that the limits of beneficial application will embrace only small ranges.

It therefore seems to me that operating results should be observed carefully and continuously for any installations of the earth coil now in service. While experience with additional installations is desirable it would, however, seem good engineering judgment that any early installations be added only in those situations that appear to offer the most favorable conditions.

Mr. Ferris in his discussion, has, very properly, touched upon the relation of this device to the problem of inductive interference control, and presented some of the theoretical aspects concerned. In this regard, also, the earth coil seems susceptible of extensive theoretical deduction as to results, but I believe that most of the foregoing points raised concerning it as a power system protective device, and other similar considerations, are applicable here and that conclusions cannot be drawn as to practical results, either beneficial or adverse, except from observations of actual performance.

To properly determine its effect upon telephone circuits, various telephone system characteristics as well as those of the power system, must be observed and given due weight. Under abnormal conditions in the power system, which I understand is the situation offering opportunity for possible benefit from the coil, the practical need for it has a very intimate relation to the characteristics of the telephone protective devices.

Any studies or tests to determine the value or need of the earth coil as an inductive interference control device should, as Mr. Ferris suggests, be made cooperatively and with all information bearing upon the subject taken to account.

In this connection it seems pertinent to inquire the status of any relatively recent research work by the telephone companies upon their protectors that may bring improved characteristics, particularly as the arrester types with which engineers in general are familiar appear to have undergone no essential change for many years.

R. D. Evans: Mr. Lewis has questioned the order of preference of the various methods of grounding the neutral of power systems when viewed from the standpoint of continuity of service. The essentials for providing for continuous service are:

1st. Employment of measures for prevention or reduction of disturbances which may result in failure of apparatus lines on equipment.

2nd. The prompt isolation of apparatus lines on equipment in case of failure.

Relay protection for the isolation of faulty parts of the power system has developed to a much greater extent than means for the prevention or reduction of disturbances. Consequently, the dependence for continuity of service is rightly placed on adequate relay protection in connection with multiple lines. For this reason, preference is given to the grounded neutral system because it best insures desired relay operation. It is generally recognized that faulty part of a power system should be promptly isolated to prevent interference with continuity of service. The earth coil system does not permit adequate relay protection and, therefore, this system does not deserve better than fourth place in the order of preference, for the various methods of grounding from the standpoint of continuity of service.

With reference to the question for the conditions of resonance mentioned by Mr. Trueblood, it is to be pointed out that this condition may be determined in two ways:

1st. By adjusting the reactor to obtain a minimum current through a fault on one wire as indicated for the single-phase system of Fig. 2 of the paper.

2nd. With normal conditions on a power system to induce a voltage in series with a series resonance system and adjust a reactor for maximum current through it.

That these two methods of obtaining resonance are equivalent may be seen by the following analysis:

If a voltage be induced in series with the reactor exactly equal to the voltage between one conductor and the ground, that conductor may be grounded without changing conditions. The introduction of a voltage on this system cannot affect the capacities, and consequently, the two conditions for obtaining resonance described above are identical.

Under the conditions shown in Fig. 25, there was undoubtedly some effect of saturation of the iron in the transformer employed to connect the earth coil in the power system. Mr. Trueblood appears to believe that the maintenance of the arcing condition was due to saturation which produced dissonance, causing the large fault currents. It appears more logical to believe that the excess voltages were produced by the arcing condition and that the excess voltages were limited by the saturation of the transformer to approximately 1.3 times normal voltage.

If the earth coil consisted of an air core reactor, higher voltages would be produced accompanied probably by relatively smaller fault currents. The use of the transformer in such a manner to reduce excess voltages has been advocated in Europe by those favoring the earth coil system.

Mr. Trueblood's careful reading of the paper has revealed two statements which we would like modified. In case of a single make and break, the voltage between the sound wire and ground may rise to slightly less than 2.73 times normal voltage between line and neutral instead of slightly less than twice line voltage. For the single-phase system the voltage of the sound conductor may rise to slightly less than three times normal voltage to ground. The context of Fig. 5 indicates that the diagram was drawn incorrectly. It should be as shown in the accompanying diagram, Fig. 2.

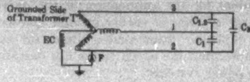


Fig. 2

Mr. Trueblood in his discussion appears to minimize the importance of excess voltages arising from abnormal conditions. He states that excess voltage between sound wire and ground will not exceed 125 per cent to 150 per cent of line voltage, these voltages correspond to 216 to 260 per cent of normal voltage between line wire and ground. Possibilities of excess voltages on the free neutral system were pointed out but the value of the dead grounded neutral in protecting insulation and draining away abnormal potentials was learned only through the costly school of experience, as Mr. Silver has just pointed out. The Petersen Earth Coil System in general approaches the characteristics of the free neutral system and both are subject to abnormal voltages. In this connection, we wish to refer to a discussion published in the E. T. Z., March 10, 1921, in which Dr. Roth cited a case where an open circuit on which wire of a 50,000-volt system produced voltages of 150,000 volts to ground due to the action of the earth coil. He further stated that these voltages, as might be expected, caused the failure of the transformer. The significance of this discussion lies in the fact that the series resonant relation is inherent in the earth coil system and that voltages may be induced in the system due to conditions such as the presence of other circuits and abnormals which can scarcely be avoided in practise. The tendency to minimize the importance of excess voltages would be as dangerous with the earth coil system as with the free neutral system.

Mr. Ferris has described some European installations of the earth coil including the opinions of the operators of the power system. In this connection, it is to be pointed out that the improvement in operating conditions secured by the installation of an earth coil is not significant unless compared with the operation of a grounded neutral system.

The inductive interference aspects of the earth coil system were considered by Conwell and myself during the preparation of the paper, and at that time, was deemed inadvisable to bring that phase of the subject before the Institute. The chief advantages of the earth coil from the standpoint of inductive interference are in comparison with the grounded neutral system. Two of the principle advantages are as follows:

1. Reduction in harmonic residual currents in normal operation, due to the high value of earth coil reactance.
2. Reduction of earth current in case of a fault.

Two of the principle disadvantages of the earth coil system from the standpoint of interference are:

1. The increase in fundamental frequency residual current, due to dissymmetry in line or load.
2. Under abnormal conditions the increase in residual voltage.

This latter point is of particular importance on inter-connected systems because with the earth coil system there is no adequate system of relay protection for isolating a faulty feeder. It would be necessary, therefore, to "hand pick" the lines to isolate the faulty feeder, and during this time the large residual voltage might produce noise interference. If such a condition arises the change from a grounded neutral to an earth coil system would change the type of interference trouble from that due to high induced voltage at fundamental frequency existing momentarily to that of noise interference lasting a much greater length of time.

More important, however, than the considerations discussed above is the general question of the desirability of the earth coil from the standpoint of the power system. If the earth coil produces troubles similar to arcing grounds or produces excessive potentials, then failure of power apparatus will follow. Hence, the application of the earth coil as an interference remedial measure is dependent, primarily, upon its satisfactory operation from the viewpoint of the power system.

The most significant fact in connection with the discussion of the merits and limitations of the earth coil system is the fact that all the power men who have expressed themselves in the discussion are in agreement on the point that the Petersen Earth Coil System is not of general application. Mr. Lewis stated that the field of the reactor at the present time would seem to be limited to moderate voltage and moderate length systems. Mr. Hanker stated that it appears that the earth coil is not suitable for general application on power systems, and that the most suitable condition for the application of the earth coil is on moderate voltage systems of rather limited extent. Mr. Warren has stated that the Petersen coil (as an interference measure) cannot be used under conditions where it is incompatible with the service requirements of the power company.

R. N. Conwell: Realizing that the Petersen Earth Coil may be considered from two points of view, the authors preferred, in this paper, to consider the device only in the field which it was originally designed to fulfill, *i. e.*, as an arc suppressing device, for the suitability of the device as a remedial measure in cases of inductive interference must depend upon its acceptability and proper functioning as a suppressor. The tests were designed to show the suitability of the device both as an arc suppressor and as a remedial device for interference to signal lines. The effect of the Petersen Earth Coil on adjacent signal lines, based on these tests, has been covered in the report of the Inductive Interference Committee, N. E. L. A. and presented at the Forty-fifth Convention, Atlantic City, N. J. May 15-19, 1922. As a result of the information obtained, both with regard to the operation of the coil on the power system and its effect on adjacent lines, it was decided that the device was not suitable for the purpose for which it was recommended.

Mr. Ferris refers to an extensive installation of the Petersen system in Switzerland and states that "the coils in this case have air cores, whereas in all other cases they have iron cores." I have been advised that some of the coils on this system also have iron cores, installed to limit the overpotentials as explained by Mr. Evans.

Some difficulty has been experienced through over-potentials in those sections equipped with air core coils, which resulted ultimately, in the failure of transformers.

It is noticable that all of the power engineers taking part in the discussion, emphasize the advantages of the solidly grounded system and since the Petersen Coil System approaches the ungrounded system in characteristics, the use of such a device appears to be a step backward.

The Effects of Moisture on the Thermal Conductivity of Soils

With a Bibliography on the Heating of Cables

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It has been appreciated for many years that the presence of moisture in the soil surrounding underground cable was of assistance in dissipating the heat generated within the cable. But little was definitely known, however, of the exact changes in the thermal conductivity of soils caused by the presence of moisture. The following article shows that moisture plays a predominant part. The relative thermal conductivity of various types of perfectly dry soils, such as sand, clay, gravel, etc., covers a range from only one to two, while he addition of moisture increases the range to five times or more that of dry soils.

The article also includes a bibliography on the heating of underground cables, giving reference to 59 papers on the subject in English, French and German.

WITHIN recent years numerous ways have been suggested of working underground cables at increased load capacities. Some of the most promising methods have been:

(a) To decrease the temperature coefficient of dielectric energy loss by improving the quality of the insulation in high tension cables, thus allowing the cables to be safely worked at higher temperatures.

(b) To use a blackened sheath, consequently obtaining a better surface radiation to the duct air.

(c) To use forced ventilation of the duct air.

(d) To fill up the air space in ducts with water, compound, etc. In fact, anything that offers better heat conduction than still air.

(e) To carry away the heat by circulating water either directly through the ducts or through piping laid in the empty spaces of the ducts.

(f) To keep the surrounding soil thoroughly soaked with water, especially at hot spots, by laying porous tile piping just over the conduit.

(g) To use very porous ducts in conjunction with a porous pipe through the center of conduit cross-section so that water would gradually seep through and in rapid evaporation to the surrounding dry soil carry away a large part of the heat.

(h) To avoid all sources of external heat such as steam mains or undue absorption of sun rays. In this particular, the black surface of asphalt streets when fully exposed absorbs a great deal of heat from the sun.

(i) Lastly, and most important of all, to study carefully each individual conduit system and determine where the hot spots are and at what period of the year they need the closest watching. By some one or a combination of the above methods the heating at hot spots can be brought down to correspond uniformly with the rest of the conduit length.

The heat conducting path is a series path through the cable insulation, duct air, duct walls, concrete shell (if any) and finally into the surrounding soil. Obviously, the relative temperature drops through the different sections of the series path will determine the effectiveness of the above cooling methods. For instance, if the greater part of the temperature drop occurred from copper to outer surface of duct walls, or concrete, there would be little gain in saturating the surrounding soil with water. Some other method would then have to be used, such as outlined in subheading (c) or (e).

Fortunately, it is now fairly well established that in the average well constructed conduit line a very appreciable part of the total temperature drop, especially at hot spots is in the surrounding soil. Anything that increases the thermal conductivity of this soil is therefore worth considering. It is the purpose of this article to describe some thermal conductivity tests made on soils containing different percentages of moisture and to compare the results with those of other investigators.

Two previous investigators have published results of interest.[1] With dry sand and soils the agreement between their thermal conductivity values is good but there is a very great difference with wet sand and soils. Kennelly found that the thermal conductivity of wet sand was 2.4 times that of dry sand and that the thermal conductivity of wet sandy soil was only 1.3 times that of dry sandy soil. Teichmuller, on the other hand, found a corresponding ratio for sand of 5.2 to 1. Now, it is apparent that if Kennelly's results are correct artificial soaking of soil would not prove a very effective means of cooling. Tiechmuller's results are much more encouraging. Our work was undertaken to determine why there was such a large discrepancy in their findings and, in particular, to make a closer study of moisture effects.

Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

1. "Heating of Copper Wires," Kennelly and Shepard, A. I. E. E., Vol. 26, 1907, pp. 969-995.

2. "Heating of Cables," Teichmuller and Human, *E. T. Z.*, June, 1906, p. 579.

SUMMARY OF RESULTS

Profiting by the experience of the above investigators we were able to design our apparatus and conduct tests in a way that promised reasonably satisfactory returns. Before going into the details a summary will be given and a comparison made with the work of Kennelly and Teichmuller.

Thermal Conductivity of Sand. We first made a laboratory study of a representative unsifted builders sand. It was neither coarse nor fine but of medium texture and all pebbles of appreciable size were removed. When well tamped the amount of moisture required to saturate it completely was more than 15 per cent by weight but the sand would not hold this moisture long enough for test purposes, allowing some of it to drip gradually out of the test cylinder. From 9 to 10 per cent moisture by weight seemed to be the highest practicable amount. Teichmuller also found this to be true but Kennelly gives test data with 12. 7 per cent moisture for a fine sifted quartz sand, mesh 0. 25 mm. The much finer texture of his sand no doubt held the moisture better than the coarser sand we used. The practical lesson learned from this is that sand of the ordinary kind surrounding conduit lines cannot be expected to hold more than 10 per cent moisture without draining due to gravity unless water is continuously supplied either naturally or artificially.

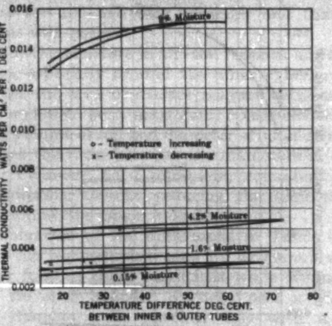

FIG. 1—THERMAL CONDUCTIVITY OF BUILDERS SAND

The curves represent the thermal conductivity of four samples of sand having respectively 9 per cent, 4.2 per cent, 1.6 per cent and 0.15 per cent of water by weight. The unit of thermal conductivity is defined as the watts flow of heat per square cm. per one deg. cent. temperature drop per cm. length.

After preliminary trials and checks of accuracy the curves given in Fig. 1 were taken on the builders sand described above. Each point on these curves represents a continuous run of about 24 hours. It required three months to complete the set of curves in Fig. 1 alone. The entire work extended over a period of more than one year. The water-jacketed cylinder used in this work is illustrated in Fig. 2 and will be dealt with in detail later.

FIG. 2—APPARATUS USED IN DETERMINATION OF THERMAL CONDUCTIVITY OF SOILS

The near end of the tube is open for the removal of the soil sample. The felt, and the ring, which holds it in place over the end of the tube, are shown hanging on a bolt just under the brass tube. The wood plug which fits in the end of the tube is shown on the corner of the table beside the contact-making voltmeter. Tests were made with tube in a vertical position.

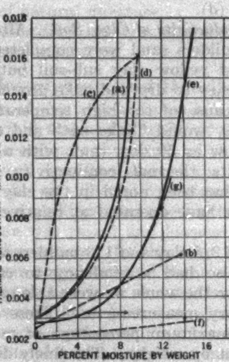

FIG. 3—COMPARISON OF THERMAL CONDUCTIVITY OF SAND AND SOIL AS MEASURED BY THREE DIFFERENT INVESTIGATIONS

(*a*) Clean yellow builders sand. (Author.)
(*b*) Fine white quartz sand, mesh 0.25 mm. (Kennelly.)
(*c*) Clean yellow sand. (Teichmuller.)
(*d*) Curve (c) reconstructed.
(*e*) Yellow sand clay soil. (Author.)
(*f*) Fine sandy soil. (Kennelly.)
(*g*) Normal or average sandy soil. (Teichmuller.)

The values in Fig. 1 were averaged and plotted as a thermal conductivity vs. per cent moisture curve in

Fig. 3 (see curve "a"). Now let us compare this curve with similar curves for sand obtained by Kennelly and Teichmuller. Kennelly used a fine grain quartz sand sifted through a 0.25 mm. mesh. His curve is given as (b) in Fig. 3. It would be expected, as will be shown later, that this curve should show slightly lower thermal conductivity than (a) because of the finer grained sand. With low moisture content (from 0 to 2 per cent) the agreement between (a) and (b) is reasonable but at higher percentage moisture the curves rapidly diverge.

Teichmuller used an ordinary sand, presumably similar to ours. His curve is given as (c). The thermal conductivity values agree almost exactly with ours at extremely low and high moisture contents. His intermediate value of 4.2 per cent is much higher however, giving his curve a different shape. The fact that the disagreement in only with the intermediate percentage of moisture content is significant in the light of our experience. We had a great deal of trouble in obtaining reliable data over this intermediate range of moisture content. The moisture had a tendency to migrate in the test tube, accumulating at one section and leaving another dry. These unstable conditions caused inaccuracies that were overcome only after several trials and a close study of "cause and effect."

If the 4.2 per cent moisture point on Teichmuller's curve (c) is ignored a curve can be constructed through the remaining two points that almost coincides with our curve (a). This reconstructed curve is shown in broken line as (d).

Thermal Conductivity of Clay Soil. After the measurement on builders sand were completed we tried a well pulverized yellow clay sub-soil but soon found it had a tendency to dry and cake around the heated inner tube because of the high temperature gradient here. The clay would "bake out" and cake at temperatures as low as 50 deg. cent. with a considerable decrease in its thermal conductivity. This same characteristic has been noted in the clay surrounding duct lines that have operated at relatively high temperature.

A mixture of 2/3 clay and 1/3 builders sand was then tried. This also had a tendency to cake in some instances but on the whole we were able to obtain some very satisfactory measurements. These are given in Fig. 4. The maximum percentage of moisture tried was 15 per cent by weight. The finely divided sandy soil seemed to hold moisture much better than the pure sand used in the first test, allowing this higher moisture content. The saturation point was higher than 18 per cent. A lower percentage of water was used to be on the safe side and to avoid instability of results by leakage of water during test.

The condition of the soil, the percentage and distribution of moisture, etc. were noted before and after each run. During the runs with 0.89, 3.87 and 15.0 per cent moisture all conditions remained quite stable throughout, but the run with 8.5 per cent moisture was disappointing. The moisture migrated to the outer radius of the tube leaving a dry shell of soil surrounding the inner heated tube. This point was therefore ignored in drawing curve (*e*) in Fig. 3. As can be seen from the curve the migration of moisture had the effect of lowering the 8.5 per cent point of thermal conductivity from 0.0056 to 0.00335 watt flow of heat per square cm. per one deg. cent. temperature drop per cm. length. (In brief, watts/cm.^{3}/one deg. cent).

Kennelly's curve for sandy soil is given as curve (*f*) in Fig. 3. It shows hardly any difference between dry and saturated soil and is likewise much lower in thermal conductivity than our curve (*e*). Curve (*f*) is similar in form to his curve for sand (*b*) and the relative proportions of these two curves fall in about the same order as our curves (*a*) and (*e*).

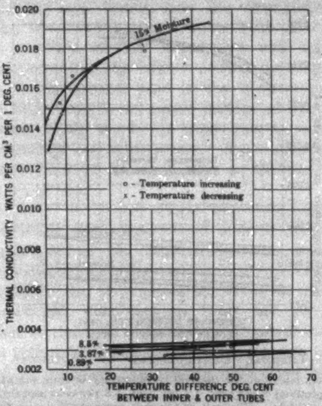

Fig. 4—Thermal Conductivity of Sandy Clay Soil

The curves represent the thermal conductivity of four samples of soil having respectively 15 per cent, 8. 5 per cent, 3.87 per cent and 0.89 per cent of water by weight. The unit of thermal conductivity is defined as the watts flow of heat per square cm. per one deg. cent. temperature drop per cm. length.

Teichmuller published only one measurement on a soil which he designates as "normal" or "average" soil. It is presumably an average sandy clay soil such as usually found in trenching or excavating. His one measurement was made with 12 per cent moisture in the soil and using this as a guide we have drawn in a short section of curve (*g*) in Fig. 3 to show how closely it can be made to agree without corresponding curve (*e*).

On the whole, our results and Teichmuller's agree satisfactorily. We do not claim absolute accuracy for these results but when the conditions of test are carefully considered it would seem that they are more accurate than Kennelly's. All three investigators followed similar methods in that they made use of concentric cylinders with the soil packed in between. The inner cylinder served as the source of heat and the outer was water-jacketed. End effects were corrected for in all cases. The real difference lay in the cross-sectional dimensions of the cylinders. These dimensions are tabulated below:

TABLE 1

Investigator	Length of outer tube Ft.	Diam. outer tube In.	Diam. inner cylinder In.
Kennelly	9.1	3.06	0.128 & 0.045
Teichmuller	12.5	7.90	2.05
Author	7.0	6.00	1.00

In an investigation of this type the cross-section of soil tested is relatively small and because of this the aim should be to assure;

(1) That there is always good contact between the surfaces of the soil and test terminals and that the soil remains well packed.

(2) That the moisture in the soil remains uniformly distributed, especially around the inner cylinder.

(3) That the area of surface contact between soil and inner cylinder be a maximum, consistent with a reasonable volume of soil and diameter of outer cylinder.

(4) That the ratio between the diameters of outer and inner cylinders be a minimum, consistent with above conditions, thereby reducing the temperature gradient around the inner cylinder.

An examination of the dimensions in Table I will show that the test cylinders used by Teichmuller and the author fulfilled these conditions while Kennelly's did not. As inner cylinder Kennelly used a wire of 0.128-in. diameter. He checked this with a still smaller wire of 0.045-in. diameter and found that they gave the same results. The reason for this is easily explained. The high temperature gradient in the soil immediately surrounding the wires forced the moisture towards the outer cylinder, leaving a shell of dry soil around the wires. In both cases, then, he actually measured the thermal conductivity of an inner shell of dry soil and outer shell of moist soil, and since the inner shell plays the predominating part his measurements are more representative of dry soil than wet. His measurements on well dried sand and soils are more acceptable and agree quite well with those made by the other two investigators as shown in Table II.

TABLE II

Thermal Conductivity of Dry Sand, Soil, etc.

Material	Investigator		
	Author	Teichmuller	Kennelly
Clean yellow sand	0.00305	0.00310	..
Clean white sand (fine)	..	..	0.00256
Yellow sandy soil	0.00280	..	0.00284
Fine sandy soil	..	..	0.00209
Crushed quartz (mesh 0.85 mm.)	..	..	0.00337
Fine sandy gravel (mesh 0.5 mm.)	..	..	0.00290
Clean gravel	..	0.00436	..

The above tabulation would indicate that the dry thermal conductivity is somewhat dependent upon the size, shape and arrangement of the particles making up the material, or rather upon the volume of air interspaced with the particles. Coarse grained materials such as sand and gravel have better thermal conductivity than fine grained soil, just the opposite result that one might expect, but it is a known fact that within certain limits the percentage by volume of air in granular materials is inversely proportional to the size of the particles. We made no attempt to investigate this phase of the problem and it is pointed out simply as an interesting side light.

A comparison of the above tabulation of dry soils with the moisture curves in Fig. 3 will show that moisture is the predominating factor rather than the kind of material. The thermal conductivity of the dry soils covers a range from 0.002 to 0.0047 watt per cm.^{3} per one deg. cent., while the addition of moisture caused an increase to 0.017 and would have caused a still further increase if the test samples had been completely saturated. This would lead to the conclusion that it is immaterial what kind of soil surrounds a conduit line except in-so-far as the ability of this soil to absorb and retain moisture is concerned.

The investigation has proved conclusively that the presence of moisture in soils is very effective in conducting heat away from underground lines. Further study should be directed towards determining:

(1) Those soils that are best adapted to absorption and retention of natural moisture.

(2) Those soils that are best adapted to artificial means of moisture saturation.

Part II—Description and Details of Test

The first part of this article covers in a general way the more important and useful results of the investigation. In this second part the details will be dealt with.

When the work was first started the results were very erratic. As an illustration, some preliminary measurements on builders sand are plotted in Fig. 5. The temperature was raised and lowered in steps, as indicated by the arrows. In this way one or more "heat cycles" were completed and if the measurements and test conditions had been accurate and stable the "heat cycles" would have been narrow and uniform, similar in appearance to those in Figs. 1 and 4. Instead the measurements plot in a haphazard manner, especially those on very moist sand. By a process of elimination this erratic behavior was found to be due to:

(a) The high temperature to which the inner tube was heated, which caused the moisture to vaporize and then condense against the cold wall of the outer cylinder. A temperature of the inner tube of about 80 deg. cent. seemed to be the highest for accurate results.

(b) During the preliminary work we had no means of constant current control of heating element. Even small fluctuations of current caused appreciable errors.

(c) The outer and inner cylinders were not connected together, electrically and grounded, at one end. Consequently when the sand was moist it furnished a resistance parallel to the inner tube and in attempting to measure the resistance of inner tube for determination of temperature an error was introduced.

(d) The inner tube used in preliminary work was of brass. The temperature coefficient of brass is smaller than that of copper and change in resistance, even when carefully measured with potentiometer, would not accurately indicate small changes in temperature. This trouble was eliminated by substituting a copper tube.

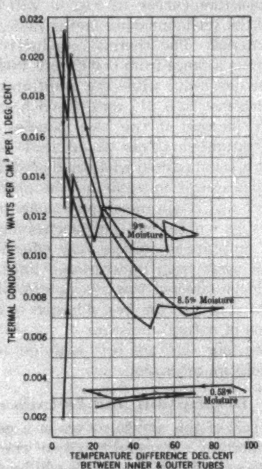

Fig. 5—Preliminary Measurements on Builders Sand

Showing the erratic results due to errors in testing methods. The arrows indicate the order of the respective readings.

The test equipment as finally developed is illustrated in Fig. 2. A dimensional sketch and a wiring diagram are shown in Figs. 6 and 7. A contact-making voltmeter held the heating current very steady. The cooling water for the jacket was taken from the city pipes and proved to be of very constant temperature (about 15 deg. cent.).

The resistance of the inner copper tube was carefully calibrated in an oil bath at different temperatures and the temperature drop across the soil under test was determined by subtracting the temperature of the inner tube, as measured by resistance, from the temperature of outer tube, measured by thermometers immersed in the water bath.

The general procedure was to place the concentric cylinders in a vertical position and fill the interstice with properly prepared soil, packing it down firmly during filling with a concentric disk spacer. In this way the inner cylinder was accurately centered. The cylinders were left in a vertical position throughout the heat run as we found this gave more satisfactory results. There was not only a better circulation of the cooling water but also the moisture in the soil would remain more uniformly distributed around the inner cylinder.

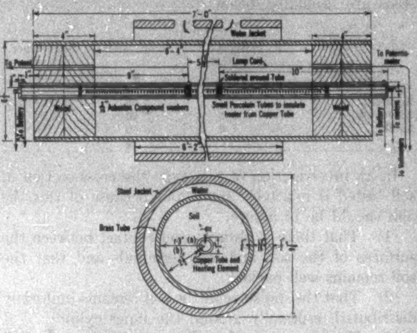
7'-0"
Water Jacket
4"
6'-4"
5"
Lamp Cord
9"
10"
Soldered around Tube
To Potent.
To Potentiometer
1"
Wood
Asbestos Compound washers
Small Porcelain Tubes to insulate heater from Copper Tube
To Battery
To Voltmeter
6'-2"
Steel Jacket
Water
Soil
Brass Tube
Copper Tube and Heating Element
(a)
(b)

Fig. 6—Dimensional Sketch of Test Tube

It required on an average about four hours to reach constant temperature conditions but for convenience and also to be on the safe side we usually let the run continue over night, taking all measurements the next morning.

Credit and appreciation are freely given to Dr. C. P. Steinmetz and Mr. J. L. R. Hayden for their valuable advice and aid in this work, and to Mr. D. A. Ballard for his untiring assistance.

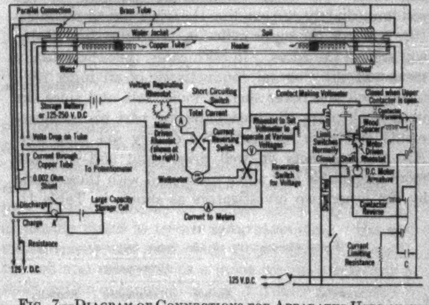
Parallel Connection
Brass Tube
Water Jacket
Soil
Copper Tube
Heater
Wood
Wood
Voltage Regulating Rheostat
Short Circuiting Switch
Contact Making Voltmeter
Closed when Upper Contactor is open.
Storage Battery or 125-250 V. D.C
Total Current
Motor Driven Rheostat (shown at the right)
Current Reversing Switch
Rheostat to Set Voltmeter to operate at Various Voltages
Contactor Forward
Wood Spacer
Limit Switches Normally Closed
Motor Driven Rheostat
Shaft
Volts Drop on Tube
Current through Copper Tube
To Potentiometer
0.002 Ohm. Shunt
Wattmeter
Reversing Switch for Voltage
D.C. Motor Armature
Discharge
Large Capacity Storage Cell
Charge
Current to Meters
Contactor Reverse
Resistance
Current Limiting Resistance
C
125 V.D.C.
125 V.D.C.

Fig. 7—Diagram of Connections for Apparatus Used in the Determination of the Thermal Conductivity of Soils

Appendix

Heating in Underground Cables

The foregoing laboratory work on the thermal conductivity of soils was completed a year and a half ago.

The results were not published at that time but were made available to engineering committees and operating companies actively engaged in a study of heating in underground cables. Publication at the present time is prompted by the Preliminary Report of the British Electrical Research Association on "The Heating of Buried Cables," which appeared in the *Journal* of the I. E. E., February, 1921. Recognition was made in this admirable and extensive report of the influence of moisture in the soil surrounding buried cables. No substantiating data, however, were submitted and it is felt that the present article contributes something in that respect.

Heating in underground cables has received a great deal of theoretical and practical consideration in the past and many articles have been published on the subject. During the course of our work a thorough canvass of the literature was made and a bibliography prepared containing reference to articles that throw light on the problem. The bibliography is given with the present paper in the hope that it may prove useful to other engineers.

Although this bibliography covers a great amount of work it is surprising how little progress has actually been made in placing the theory and practise of heating in cables on a practical working basis. In the writer's opinion this is due to a lack of coordinated and systematic effort. The problem is big and requires a really tremendous amount of coordinated work to place it beyond the preliminary stage in which it is now. The work undertaken by the British Research Association is a step in the right direction and should be supported by similar work in other countries.

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Discussion

D. W. Roper: As Mr. Shanklin stated, the British Research Association is doing similar work along these lines, and their results show some variations that were unaccounted for, and which, perhaps, may be solved by Mr. Shanklin's data.

Their tests were all made on buried cables, out in the open, where the effects of moisture must have varied from day to day, and the tests extended over a period of several weeks or months, and apparently it must have rained now and then during that interval, so I think that some of the variations they discovered and did not account for in the heating of the cables would be accounted for by Mr. Shanklin's data showing that the percentage of moisture in the soil has a considerable influence.

In the latter part of his paper Mr. Shanklin states that the work of the British Research Association should be supported by similar work in other countries. In this country we have had for two or three years a Cable Research Committee of which the speaker is the Chairman, and which is a sub-committee of the proper technical committees of the American Institute of Electrical Engineers, the National Electric Light Association, and the Association of Edison Illuminating Companies.

We have recently undertaken an investigation on the maximum permissible temperature of paper-insulated lead-covered cables, and we were prompted to do that by the remarkable differences of opinion which were expressed at the symposium on the subject before this Institute at the Convention a year ago. We have, therefore, secured a fund for research and have arranged with the Massachusetts Institute of Technology to conduct the investigation on this question of maximum permissible temperature, and it may be of interest to you to learn that the first check covering the expense of the research has been forwarded to the Massachusetts Institute of Technology, and we are meeting with the research men today to start the investigation.

R. W. Atkinson: The author has rightly emphasized moisture as of far greater importance than any other variation of soil conditions.

Until we have complete data of underground conditions, such as this paper shows to be necessary, in order to be safe when designing new underground systems we must estimate carrying capacities by taking into consideration the conditions of poorest present systems.

Data on these variables will make it possible to predict conditions, to design cheaper systems and help in their operation. If conditions are found unfavorable steps may be taken toward improving them.

W. A. Del Mar: It is somewhat difficult to see how this work of Mr. Shanklin's can be applied to practical use at the present time, because we have no control over the soil conditions or over the moisture conditions, so that in estimating the carrying capacity of cables, it is in general necessary to assume very bad conditions of soil conductivity.

There is, however, another property of the soil which is of considerable importance, and that is the thermal capacity or specific heat. The carrying capacity of a cable is very much influenced by the thermal capacity of the soil. Usually a cable is operated at its full load only for a very short period of the day—during the hours of peak load—and the thermal capacity is of great importance, because it determines the overload capacity of the cable during the peak period. It is unfortunate that Mr. Shanklin did not give the thermal capacity of the soil at the same time. It might possibly be derivable from his test data, even now.

In Europe, cables are very largely buried in the ground without being placed in ducts, and it is obvious that the influence of soil moisture will be greater in the case of such cables than in the case of cables in ducts, because in the latter case there is necessarily a more or less dry layer through which the heat must escape in getting from the cable to the soil. When armored cables are buried in the soil, and the soil is fairly moist the carrying capacity is surprisingly greater than in the case of cables laid in ducts in ordinary soil. I have not the figures with me, but they are available in existing literature, and in many cases it is worth while to look into the advisability of burying the cables directly in the ground to obtain the extra carrying capacity.

G. E. Luke: The determination of constants which limit the flow of heat is theoretically very simple; practically, however, such problems offer many difficulties and can be solved only by an untiring patience. This is especially so in this investigation described by Mr. Shanklin, where the unstability of the moisture content of the soil gave considerable trouble.

The conductivity curves Fig. 1 and 4 seem to indicate a decreasing thermal conductivity of the moist sand and soil as the heating continues. I take this to be due to a possible loss of moisture or a re-arrangement of the moisture in the material. Since the conductivity of dry sand clay soil was only 0.0028 w/cm.^{3} deg. cent. and that of water about 0.0057 it indicates that the high value of 0.014 to 0.020 obtained on the 15 per cent moisture mixture was due to convection currents in the water.

The rapid decrease of the co-efficient of thermal conductivity with increasing temperature gradients for the 15 per cent moisture mixture also indicates convection currents, since the heat transfer curve for a steam heated pipe in a tank of water has a somewhat similar shape. Due to this convection, it is probable that the co-efficient of thermal conductivity will depend to some extent upon the depth of the moist soil through which the heat is flowing. It would be interesting in this connection to explore the moist soil temperatures radially in the sample tested and thus be able to see if the co-efficient of thermal conductivity remained constant for various points distant from the heater.

The author mentioned the fact that some difficulty was encountered in the measurement of the inner tube temperature by the resistance method. The writer has had similar experiences in experimental tests and prefers to measure temperatures of such inaccessible places by thermocouples.

This investigation shows the possibilities of reducing the cable temperatures by moist soil. Of the other methods mentioned by the author the most promising ones are by the use of forced air or water streams through the cable ducts.

C. J. Fechheimer: The author states on the first page that it is possible by blackening the sheath to dissipate somewhat more heat. I wonder whether that was appreciable. The increase in heat dissipation due to blackening must come in consequence of the increase in radiation. I am of the opinion that the amount of heat that is dissipated by radiation is comparatively small, because the heat thus dissipated is proportional to the difference between the fourth powers of the absolute temperatures; and unless there be considerable differences in temperature, not much heat is dissipated by that means. In general most of the heat that is dissipated at ordinary working temperatures from cables or even from the outside surfaces of machines, or from self-cooled transformers, is brought about by natural or free convection currents of air, rather than by radiation.

This question of natural convection currents brings up a second point, namely, the influence of air pockets in affecting the thermal conductivity of almost any kind of material in which such air pockets occur. The influence of such air pockets changes very materially with their size. If the air pockets are very minute, heat that passes through them must flow by thermal conduction, whereas when they become of any considerable size, some natural convection currents are added. It is well known that if the air pockets are, say, one-tenth of an inch across more heat is transmitted by natural convection currents than by conduction. That is a very important point in all thermal conductivity problems; the influence of air pockets must be considered very carefully.

The author speaks of the size of the granules and states that the larger the granules, the better is the thermal conductivity. If I read his paper correctly, I understand him to attribute this to the fact that the volume of air which is entrapped between granules is smaller the larger the granules are. That probably accounts for some of the difference, but I am of the opinion that the thermal conductivity was altered more by the fact that with larger granules the air pockets were larger, and therefore the natural convection currents were considerably greater; consequently the apparent conductivity of the coil was increased.

It is interesting to note also, in Fig. 3 in the paper, the rapid increase in thermal conductivity as the percentage moisture is increased for the higher values of moisture. As water begins to displace the air particles that are trapped between the solid particles of the soil, the thermal conductivity is not increased very much—there are still enough air pockets to offer considerable resistance to the flow of the heat. It is only when the voids begin to become negligible due to the last water that is forced into the soil, that the thermal conductivity is raised considerably. Perhaps that may account for some of the discrepancies between Mr. Shanklin's tests and those of the authors to whom he refers.

The question of air pockets comes up very frequently, indeed, in engineering practise. For instance, in the building of houses it is well known if hollow tiles are used, and the air pockets are very large, the apparent thermal conductivity is fairly high; but if some finely divided material such as sawdust is put in, so as to make the individual air pockets quite small, then the thermal conductivity is materially increased, and less fuel is required to heat the building.

Nature has also taken care of this matter of air pockets in the manner in which some of the animals have been provided with clothing—for instance, the sheep with wool, or the duck with its type of feathers, eiderdown, both of which are known to possess very low thermal conductivity, for the reason that the air pockets are quite minute.

G. B. Shanklin: In reference to Mr. Roper's remarks, I am cognizant of the valuable work just started by his Cable Research Committee and am sure all members of the Institute anticipate great things from this work. Regarding the work of the British Research Association, Mr. Roper is right in accounting for some of the variations in results as due to moisture content of the soil. In any study of thermal characteristics, the distribution of moisture must be known, and preferably under control. This is particularly so where cable is buried directly in the ground.

I agree with Mr. Del Mar that parallel data on thermal capacity of soils containing different percentages of moisture are equally desirable. It is unfortunate that the procedure of our work made it impossible to obtain complete heating and cooling curves, necessary in determining thermal capacity. In a few cases we did get complete heating curves from which at least an approximate idea of thermal capacity can be derived. Without careful checking, however, these data could not be relied upon.

Mr. Fechheimer's discussion of air pockets is quite timely. It is generally recognized that they play an important part. In this respect the variations in thermal conductivity of paper insulated cables should be borne in mind. The degree of filling and looseness of lead sheath account almost entirely for these variations.

Five Hundred Tests on the Dielectric Strength of Oil

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While developing a dependable method of taking experimental data with a sphere gap in transil oil, considerable study was made of the behavior of oil under disruptive dielectric stress. The following notes on the dielectric strength of oil are offered as evidence that the nature and character of the dielectric breakdown of oil may be entirely different from that of air.

Five hundred successive breakdowns were taken on a sphere-gap in oil at the same gap setting. Because of the well known inconsistency of breakdowns in oil these observations showed wide variation. A curve was plotted to show the relation between the breakdown voltage and the number of breakdowns at each voltage. If the disruptive breakdown of oil is due to the voltage exceeding the dielectric strength of the oil, as is the case with air, it should be possible to represent such a curve of probable error, or "probability curve" as it is usually called, by an exponential equation. In the following paper this is seen to be impossible, the most representative exponential curve being higher than the observations at higher voltages. The explanation is offered that this discrepancy is caused by foreign particles of low dielectric strength being drawn into the gap and that therefore the dielectric strength of oil differs from that of air in that it does not represent the true breakdown value of the oil but is instead a measure of the presence of foreign particles in the oil.

AIR gives a definite dielectric strength (30 kv. per cm. at 0 deg. cent., 76 cm. barometer), as shown by the work of Peek, Ryan and Whitehead, and disruptive tests in air gap give consistant results within the errors of observation. Not so, however, oil. In spite of the greatest care taken to reproduce identical conditions as nearly as possible, successive disruptive tests made on the same oil differ from each other far beyond the possible errors of observation.

To study this phenomenon of the erratic behavior of oil, and its possible cause and explanation, 500 successive tests were made with the same sample of oil under constant conditions. A large sample of oil was chosen, the circuit opened immediately after each discharge, and the discharge current limited by resistance in the low-tension circuit, so as to give little deterioration of the oil (by carbonization, etc.) during the test, and the deterioration allowed for, as further described. In commercial testing of oil, usually small flat disks with sharp edges are used as electrodes, to give a combination of the effect of a uniform field and the edge effect. When, however, determining the dielectric strength of a material, as nearly a uniform field as possible must be used, and a field which can be accurately calculated. This is the case with the field between spheres at moderate distance from each other. Therefore a sphere gap was used. In view of the high dielectric strength of oil, and to avoid excessive voltage a gap of two mm. was used between spheres of one cm. diameter. The spheres were of molybdenum, as experience had shown that tungsten and molybdenum are least liable to pitting under the discharge. After each test the spheres were wiped off in the same manner, under the oil, by a wiper kept under the oil and the oil allowed to settle the same length of time before each test. The oil was filtered hot through a number of layers of hot and dry filter paper, and carefully protected from dust and moisture. The same source of voltage supply, 60-cycle alternating current, and the same transformers were used, and the voltage controlled by the potentiometer method (shunt and series resistance), being the method least liable to give voltage wave distortion. The voltage was raised at the same constant rate in all tests, one volt per second on the low-voltage side of the transformers, at a transformation ratio of 580; in short, the conditions were kept as nearly the same as could be determined, and much more uniform than is necessary to get consistent results in air. The voltage was read on the low-tension side of the tranformers, as this checked to be accurate within less than one per cent.

Nevertheless, the observed breakdown voltages in the successive tests differed enormously, and in entirely erratic manner, by as much as a hundred per cent.

In spite of the large volume of oil used, there was a slight deterioration which became noticeable after more than 200 tests. Therefore the tests were divided into five successive groups of one hundred each, and the average value calculated for each hundred. This gave the average breakdown voltages (low-tension side, ratio 580 to 1) for the successive five sets of hundred tests,

$$e_0 = 95, 96, 91, 89, 86$$

showing a slight and increasing deterioration.

To allow for this, in working up the tests, not the voltage e of each individual test was used, but its difference from the average voltage of the hundred tests to which it belonged, that is $x = e - e_0$.

Using these differences $x = e - e_0$, the effect of deterioration was sufficiently eliminated, and all 500 readings could be combined. The number of breakdowns y observed at each voltage difference x is given in the second column of the following table, and plotted as y in Fig. 1, marked by circles, with x as abscissas.

As seen, the values of y do not lie on a smooth curve, but vary erratically, but their grouping is similar to that which would be expected from a set of values scattering by probability around an average value.

Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

TABLE I

$x = e - e_0$	y:	$x = e - e_0$	y:	$x = e - e_0$	y:	$x = e - e_0$	y:
− 31	0						
− 30	2	− 17	1	− 4	14	+ 9	20
− 29	0	− 16	2	− 3	19	+ 10	16
− 28	2	− 15	0	− 2	19	+ 11	10
− 27	0	− 14	5	− 1	20	+ 12	14
− 26	0	− 13	11	0	32	+ 13	10
− 25	1	− 12	10	+ 1	14	+ 14	9
− 24	1	− 11	7	+ 2	17	+ 15	6
− 23	3	− 10	14	+ 3	30	+ 16	2
− 22	1	− 9	11	+ 4	25	+ 17	2
− 21	1	− 8	8	+ 5	23	+ 18	1
− 20	4	− 7	14	+ 6	18	− 19	0
− 19	2	− 6	23	+ 7	23	+ 20	2
− 18	2	− 5	9	+ 8	20	+ 21	0

A number of probability curves were calculated by the $\Sigma\,\Delta$ method[1], in the attempt to fit the relation between x and y.

It was found that all the data could not be represented by one probability curve, but the probability curve calculated from the positive x values—that is, the voltage e above the average e_0—did not fit the negative x values, and inversely.

However, the y values from $x = +9$ to $x = -22$, comprising 84 per cent of the observations, can be well represented by the probability curve

$$y = 24.8\,\epsilon^{-0.0051(x-3)^2}$$

This probability curve is shown in Fig. 1. It fits the observations fairly well, except that for high values of voltage, the observations drop below the probability curve, the more so the higher the voltage; that is, the breakdown occurs at lower voltage than given by the probability curve. At very low voltages, the observation seem to be higher than the probability curve, but in this range their number is too small to be conclusive.

The explanation which suggests itself is as follows:

The disruptive breakdown of oil under dielectric stress is not due to the voltage exceeding the dielectric strength of oil, as is the case in air, but is due to something being carried into the dielectric field, or being produced in the dielectric field, which weakens the dielectric strength so as to cause a premature breakdown. The breakdown therefore does not occur at a definite value of voltage, as is the case with air, but at values scattered over a wide range of voltages in accordance with the probability curve of the appearance of such dielectrically weaker material in the field. What this material is, we do not know; it may be moisture, or dissociation products of the oil, or olefines or fats or fatty acids, or dust or fibers, or combinations of them, in solution or collodial solution or suspension in the oil.

On the higher-voltage part of the probability curve, the approach to the true dielectric strength of oil increases the frequency of breakdown beyond the probability curve, and thus causes the observations to drop below the probability curve. This also causes the maximum point of the probability curve to be at a higher voltage than the average breakdown voltage..

This opens up a very interesting, and in view of the great industrial importance of oil as insulating material, important field for further investigation. Hitherto, usually the assumption has been made that the dielectric breakdown of oil and other similar insulations is of the same nature and character as that of air, that is, it depends upon a definite breakdown value, though the experimental behavior of oil in the dielectric field, such as its erratic breakdown voltage, the very pronounced time lag, etc., point to the possibility that the mechanism of the dielectric breakdown of oil and similar materials is materially different from that of air.

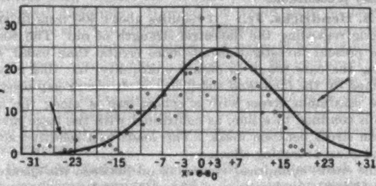

FIG. 1—PROBABILITY CURVE OF DIELECTRIC BREAKDOWN OF TRANSIL OIL AND THE PLOTTED VALUES OF THE OBSERVED TESTS.

The ordinates (y) are the number of punctures that have been found, by observation, to take place at each value of the abscissas.

The abscissas are the difference between the particular average value and the actual value of puncture voltage for each test. The numerical values are given in low-tension volts. The actual voltage difference may be found by multiplying the particular abscissa by the transformer ratio, 580 to 1. Thus the maximum difference from the average breakdown (say 55,000 volts = 95 × 580) is minus 31 volts which is actually 18,000 volts less than the average puncture value of 55,000 volts.

On the other side of zero, the highest puncture voltage above the average is 21 which corresponds to 12,200 volts = 21 × 580. It should be noted that all the observations in this neighborhood fall far below the solid line, which is the mathematical probability curve given by the particular formula

$$y = 24.8\,\epsilon^{-0.0051(x-3)^2}$$

This equation, by several trials, was found to be the nearest obtainable representation of all the values given by the tests and shown by the circles.

Discussion

C. E. Skinner: I have been familiar with the dielectric tests of oil for a good many years, and have personally made many thousand of tests, and have been familiar with many thousands of others, but I do not think I have ever had the idea that oil could be compared to air for uniformity as an insulating medium.

Oil has a very complicated chemical structure—it carries in it many impurities, and I have frequently observed the lining up of small impurities in the oil, such as fibers, etc., and have frequently noticed that if the potential is applied for a considerable period at a value somewhat below the instantaneous breakdown, breakdown will finally occur.

Relatively high values for a group of tests insures good oil, but low values may indicate accidental troubles with the test and not necessarily poor oil unless every possible precaution has been taken. It is for this reason that we have established an oil testing service with experts in charge.

A few years ago, we in the more or less fundamental study of insulation, wished to get some material which would be as nearly constant as possible, and we undertook, as did Mr. Hayden and Mr. Eddy, to use oil. We found that only with the most extraordinary precautions could we get anything approaching uniformity of results, such as to allow the use of oil as a standard.

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[1] Steinmetz, "Engineering Mathematics," Chapter VIC.

In the commercial use of oil, we must expect a considerable variation in insulating value, and designs for its use must be so made that the average, or even the lower values, are those which are depended on, and used under extreme conditions and not those high values which can be obtained only with extraordinary precautions.

A. B. Hendricks, Jr.: It requires about 500 tests to prove anything regarding the dielectric strength of oil. The results of the present investigation are more erratic than usual, considering the care taken to obtain uniformity, but this may be explained by the form and small size of the spark gap used.

The maximum stress with a sphere gap is along the axis, hence is confined to a line, as contrasted with the large area of uniform stress between disks. This leads to a selective action instead of an averaging effect.

If the entire cylindrical volume of oil between the electrodes is considered as under stress, both volume and cross-section are much less than in the usual form of disk gap (about 1/7).

The authors state, "Usually the assumption has been made that the dielectric breakdown of oil . . . . . is of the same nature and character as that of air." If so, the assumption was in error, as the ordinary factory and laboratory tests do not give an absolute value for the dielectric strength as with air, but an approximation to the probable average value, which should be interpreted as an indication of relative purity but not as an absolute value of dielectric strength.

The dielectric strength increases and approaches a maximum value as the amount of impurities decrease and this maximum may be taken as an absolute value, but oil containing impurities has no definite dielectric strength the results of tests being a matter of chance as pointed out by the authors.

These facts lead to uncertainty and dissatisfaction in the use of oil as a dielectric and cooling medium, but it is still the best and practically the only available material for the purpose (except gases), and the defects and variations are inherent and should be recognized.

The form of spark gap now in general use as a standard has as electrodes flat brass disks 1 in. in diameter with square edges and set 0.1 in. apart. I was responsible for the design and introduction of this form and desire to give some of the considerations which led to its adoption.

It is true that the voltage gradient is indeterminate and highest at the edges and can be calculated only for simple geometrical forms, as spheres.

This may be of theoretical interest but is of no practical consequence as the absolute dielectric strength of oil is indeterminate unless pure, which it never is, and depends on the tendency to a fortuitous collection of conducting particles in more or less continuous chains between the electrodes. The oil is kept in violent circulation between and near the electrodes, when approaching the arcing voltage, so that the chains are continually being formed and ruptured.

"It stands to reason, is a well known fact, and is obvious" that the stress is greatest at the corners and that the arcs tend to form there. The trouble with this imaginary statement is that it is only partly true, the actual effects being quite different from those which might be expected from superficial considerations.

Breakdown does not necessarily occur at points of maximum stress, as on corners, nor along the shortest path. It occurs at the time and place where the stress first exceeds the dielectric strength, the time element being important since the voltage is usually increasing at a rapid rate and the arcing voltage varies more or less inversely with time.

There is a large and nearly uniform field between disks and the effect of the edges seems unimportant in practise. I have just examined the disks from a standard spark gap which has been used for about 15,000 tests (one shot only on each filling) during the last two months. These show but slight burning from the arcs, which were confined almost exclusively to an area about ¾ in. in diameter at the center of the disk. A zone about ⅛ in. wide at the edge shows little evidence of arcing, but arcs occur quite frequently from the cylindrical surface. The samples come in quart cans, the spark gap being filled five times from each can, and one shot taken on each filling. The average of five shots is taken as representing the contents of one can. The ordinary variation of single shots from the average is about 10 per cent plus or minus and seldom exceeds 20 per cent. The maximum average value of five shots is about 40,000 volts, and there is reason to think that this represents closely the absolute dielectric strength of the oil for 0.1 inch, although the tests are between disks.

This form of gap was adopted as combining the greatest number of advantages after long experience with other forms and careful comparison with the previous standard which consisted of 0.5 inch disks 0.2 inches apart. The latter gap was used with a much larger volume of oil, it being standard practise to take five shots on one filling, stirring the oil before each shot. This older form (introduced by J. A. Capp) was used in determining the effect of water on dielectric strength, the resulting curve being widely published (See Pender's Handbook). In this test 11 points on the curve were determined, each by 5 shots on 8 samples or 440 shots for the curve, the results being quite regular and consistent and being duplicated at another time on a different kind of oil and by another operator.

The results gave a straight line on logarithm proper and the curve plotted from the resultant equation came on or near all the points.

The equations of the curve as originally given was

$$Y = 19.2\,X^{-0284}$$

where Y = breakdown voltage—kilovolts

and X = water—parts in 10,000 by volume.

The results may be expressed in round numbers, with sufficient accuracy by:

$$Y = 20\,X^{-1/3}$$

The regular and consistent results give confidence in the method. A careful comparison of this spark gap with the present standard one shows the latter to be fully as reliable but more sensitive. For 30 kilovolts in the old gap the new gives 15 kilovolts, but for higher values the new gap gives more than one-half the voltage, for lower values, less than one-half.

F. M. Farmer: Last evening the first discusser of the lightning arrester papers gave experimental evidence which apparently indicated that there is a certain minimum dielectric strength in all layers of air, irrespective of the thickness: that is, as the thickness of the layer is reduced, the puncture voltage falls, a minimum value is reached, and if the thickness is still further reduced, the breakdown voltage goes up again. Thus we have another example of our lack of knowledge of the molecular mechanics and the electrical breakdown of insulating materials.

Very recently a paper was published in England in which the dielectric stresses in cables is discussed. Experimental evidence is given which appears to show that the limiting feature is the minimum stress at the outside of the cable, and not the maximum stress at the conductor, which has been the most generally accepted theory.

Here, in this paper by Messrs. Hayden and Eddy, we have further experimental evidence of our lack of knowledge of just what goes on when solid and liquid insulating materials break down under dielectric stress. The phenomena and laws in regard to air are fairly well established, but our ignorance of solid and liquid insulations is very evident.

While this paper does not deal with the commercial testing of transformer oils for breakdown strength, I would like to call attention to a recent specification which has been issued by the American Society for Testing Materials. The electrodes and gap which were adopted for the dielectric strength test are one-inch flat disks with square edges and 0.1 inch separation. That standard was adopted after a series of tests involving something like 2200 determinations made by the Vacuum Oil Company, the Westinghouse Electric and Manufacturing Company, and the Bureau of Standards, in cooperation. A very careful mathematical analysis of the results by Dr. Silsbee of the Bureau of Standards showed rather conclusively that the most reliable results were obtained with one-inch disk electrodes spaced 1/10th inch apart.

Another feature of the prescribed procedure for this test is that five punctures are made on each of at least three specimens of a sample. If any one of the three averages differs from the grand average by more than ten per cent it is to be discarded and another specimen tested.

F. W. Peek, Jr.: The authors of this paper have done some very interesting work in applying the probability curve to the variation in the breakdown of oil. This apparently confirms the general belief that the variations are due to impurities. It is a well known fact that when a series of breakdown tests are made on a given oil with electrodes set at a small spacing there is very likely to be a considerable variation in the disruptive voltage. There is usually less variation when larger gap spacings are used. For instance, with a 2-mm. gap the authors find a a variation of ± 30 per cent from the average and 85 per cent between maximum and minimum. Tests that we have made show the same variation for the 2-mm. gap. With a 1-cm. gap, however, we find that the variation is ± 10 per cent from the average and 30 per cent between maximum and minimum. The variation may be much less even at small spacings, depending upon the condition of the oil and the type of the electrode.

While the variation is of theoretical interest, it is readily eliminated in practise. Skillful designers never use free oil spaces. Solid insulating barriers are always used between electrodes. Even with a 2-mm. oil space, which is smaller than is used in practise, the variation is cut in half by the insertion of a thin cambric or paper barrier between the electrodes. The variation is also less in practise because other types of electrodes than spheres are used. The spheres are the most useful electrodes in theoretical investigations because the dielectric field can be readily calculated.

The variation in free oil spaces is not surprising. There are a number or reasons why this variation should occur. In an oil gap under high stress there is the greatest degree of turbulence. The oil is forced back and forth between the electrodes. Another cause of variation is moisture and certain impurities in the oil. In a regular dielectric field the particles tend to line up along the lines of force and bridge between the electrodes. Moisture can, in fact, be separated from oil in this way and electrostatic separators have been devised and used. Occluded gases may also be a cause for low breakdown.

It is, of course, not necessary in practise to make 500 tests or even 100 to obtain the maximum, minimum and average characteristics of a given oil. The complete characteristics are in fact generally included in from 10 to 20 breakdown tests.

In practise oil is probably the most generally useful and reliable insulating material that is available.

John B. Whitehead: I have often wondered whether it would not be possible to get more uniform results on the dielectric strength of oil by observing the appearance of corona around a wire. In the case of a perfectly smooth wire in air, the appearance of corona is sharply marked, and even if the wire is soiled and has an irregular surface, it is very possible to separate the value of voltage at which streamers appear in the inequalities of surface, and the value at which corona appears more uniformly over the whole wire. It would seem to me that the same thing may be true of impurities in the oil, and that there might result greater uniformity of observations if it were possible to detect the appearance of corona in the oil. This detection of the start of corona is the only apparent difficulty.

Some years ago I set up in our laboratory an oil chamber in which a round wire was centered in a cylinder filled with oil, with the idea of studying the appearance of corona in the oil. The work was stopped largely because of the pressure of other matters, and because I ran into the difficulty of not being able to tell in a dark oil just the value of voltage at which the corona appeared uniformly. However, it would seem to be possible with little effort to obviate this difficulty. The apparatus mentioned used an optical method. A beam of light of high intensity passed through the oil and close to the surface of the wire. It is probable that a variation in the optical constants in the oil will be found in the presence of corona. I am quite sure that Mr. Hayden and his associates have worked with the corona in oil, and I think it would be interesting to have their opinion upon this suggestion.

Delafield DuBois: During 1905, I attempted a research on the dielectric strength of oil to determine the relation between dielectric strength and temperature. I found the same difficulty experienced by Hayden and Eddy, namely, that it was not possible to get consistent results for any given condition, and therefore I was not able to obtain exact data to show the variation of dielectric strength due to changes of temperature. But there were certain observations made during those experiments that may be of interest.

Breakdown voltages apparently increased as temperature increased. But on several mornings after the oil tank had been cooled over night, undisturbed, the first test gave a higher breakdown voltage than any made with the oil hot. This was taken to indicate that moisture was normally present in the gap, so that when the oil was heated the effect of this moisture became less, due to some kind of absorption by the oil, but that when cooling, undisturbed, the moisture condensed upon the sides of the tank, leaving the gap free from moisture.

With the oil cold and perhaps slightly moist, the well-known partial breakdowns of the oil gap, were, of course, noted. As to the breakdown at short intervals, and in order to study this phenomenon, the following experiment was made: With a needle gap set fairly wide, there were interposed in the gap, two parallel partitions of cheesecloth, dividing the gap into three equal parts. These cheesecloth separators were brought up flush with the surface of the oil, and on the surface of the oil a thin paper was floated. The bubbles rising from the gap were thus held under the paper, and indicated in what part of the gap they originated. It was noted that often the bubble was from the middle section of the gap only. This suggested that streamers of moisture were building out from the electrodes and that the breakdown was from their ends. It is obvious that these premature breakdowns do not become total breakdowns, because the moisture baths are at once dissipated by the passage of the current. However, when the breakdown between the ends of the streamers is half the oil gap, it is probable that the breakdown of the remaining half will follow. This explains why only a little moisture in the oil lowers the dielectric strength by half, or more than half, if the current of breakdown is not limited by resistance in series with the gap. The resistance of these moisture streamers and the series resistance of the testing set are two factors in determining breakdown. It is remarkable that such streamers should exist at all under the violent motion due to an electrostatic stress; undoubtedly all moisture brought into the field by the moving oil is captured and strongly held. Dry oil is, of course, not absolutely free from moisture, and under stress this moisture would accumulate in the gap, giving erratic results in any such tests as those made by Hayden and Eddy.

Carl Hering: In liquid conductors of mixed composition, as in some electric resistance furnaces, the so-called pinch-effect, which is an electro-magnetic force tending to crush the conductor radially,—has the peculiar property of tending to move the better conducting material to the central axis of the conductor; thus a rod of copper floated on a channel of mercury will be sucked down to the middle axis quite violently when a sufficiently large current flows.

This force is electromagnetic, it may be that a similar electrostatic force exists also, which tends to move the materials of lower dielectric strength into the more direct path of the disruptive discharge. The authors admit that such materials may exist as they no doubt exist in the form of disconnected particles, a uniformity of the results cannot be expected.

C. P. Steinmetz: The disruptive strength of insulation is one of the most important in electrical engineering.

Since the early days it was suspected that there is a definite dielectric strength similar to the rupturing strength of mechanics, although experience did not seem to confirm this.

For air, this matter was finally cleared up by the work of Mr. Peek, Dr. Whitehead and others, who proved that in air there is a definite disruptive strength which determines the breakdown of an air gap, but that the action is complicated by two additional phenomena, the energy distance and the time lag, and that these additional phenomena account for the disagreements in previous investigations.

Since that time, the same assumption has usually been made, and the conclusions and results on the disruptive strength of air gaps, have been transferred and applied to liquid and solid insulating material, such as oil, although such applicability was not proven, and experience did not well agree with the application of the laws of the disruptive strength of gases to liquid and solid dielectrics.

As I understand it, the object of Mr. Hayden's and Mr. Eddy's paper is to investigate the laws of disruptive strength of oil and the existence of a definite disruptive gradient which determines the breakdown of the oil gap, and to ascertain whether the laws of the dielectric strength of air can be applied to oil and solid insulation. The paper shows that such is not the case, and that the phenomenon of dielectric breakdown in oil or solids is different from that in air, since under conditions where an air gap gives constant results, as has been found by observation, an oil gap gives results scattered by the probability law over a range many times greater than the possible error. It also shows that the breakdown in oil and in solids is subject to additional phenomena which do not exist in air, and therefore the subject, in view of its importance, requires more extended and further investigation.

In my opinion, the results of the paper are not intended to apply to the problem of the commercial test of oil, but they deal with the question whether there is a definite breakdown strength of oil, and whether this breakdown strength determines the electrical behavior of oil. It seems to me the conclusion which must be drawn from the paper is that there probably is a definite breakdown strength of oil, but that the commercial and industrial behavior of oil is not determined by this breakdown strength, but that the actual breakdown of oil is very much below its probable dielectric strength, and is determined by a probability law—by which the impurities or whatever we may call it— determine the actual breakdown strength.

It seems to me that the additional data given in the discussion rather corroborate this conclusion by showing that where the tests are made under such conditions, that each test averages up, as by having a large section of oil gap, or great lengths of the oil gap, or barriers, etc., so that each individual test thus averages a large mass of oil, then the variations under the probability law necessarily are less, that is, the results are more consistent. As however, the paper does not deal with the commercial testing of oil, but with the question of the existence of a definite dielectric strength of oil the test had to be made under conditions where you have a definite gradient so as to know what you get, and where the gradient is as uniform as possible. This means a sphere gap. Therefore when the matter is further investigated by other investigators, I especially wish to draw this to their attention, and ask them to utilize the sphere gaps, and utilize them under conditions where the surrounding elements are as uniform as possible.

N. S. Diamant: I would like to ask the authors to tell us, if possible, the kind of oil used in these tests. It would be also well to know what some of the physical and chemical characteristics of the oil in question were. They go into a lengthy and welcome description of electrical test methods explaining how the voltage readings were accurate to within less than 1 per cent. However, it would be very useful to the profession to know also what kind of oil behaved as erratically as the oil under question. It seems to me this paper is an excellent example of how investigations should not be conducted. Personally, I can see nothing in their mathematical gymnastics and probability curve. These are very interesting elementary mathematics to my mind, but it would be very interesting to know the per cent of moisture in this oil and some of its physical and chemical properties.

It seems to me that the fact that the average breakdown voltages for the successive five sets of hundred tests was, $e_0 = 95$, 96, 91, 89, 86 shows fairly definitely at least for the sample under consideration, an increasing deterioration.

Now I would like to ask the authors if they can tell us what kind of oils show this erratic behavior for the first fifty or one hundred tests; also what they may expect in the way of average per cent variation in the values of successive disruptive voltages. As to the cause of the variation between the different successive values of breakdown voltages, I am sure they will agree that we will have to look more into the mechanism and theory of breakdown and its effect on the physical and chemical properties of oil.

J. Slepian: The authors contrast the uniform dielectric properties of air with the more erratic behavior of liquid insulating medium such as oil. With the great development in the past decade of the theory of ionization by collision in gases, a clear insight has been obtained into the mechanism of breakdowns in gases. The reasons for the uniformity of breakdown of airgaps under ordinary conditions are well known and it is even possible to produce special conditions in which airgaps will break down in quite as erratic a manner as the oil gaps described in the paper.

According to the theory of ionization by collision, electrons or charged molecules, called ions, when moving in a gas under a sufficiently high gradient may, by their impact with neutral molecules, break these latter up into new positive and negatively charged ions. These newly formed ions, if the gradient continues to be maintained, may also generate more ions by collision. Thus, starting with only a few charged particles in a gap, by the application of a sufficiently high voltage great conductivity may be developed. After a considerable number of these ions have been produced, due to the opposite directions of travel of the positive and negative charges and also their different velocities, space charges develop in the gap and the electrostatic field becomes distorted. The gradient becomes greatly increased in some portions of the gap and it then becomes possible to maintain the ionization by collision process with much lower voltage than was required to initially break down the gap.

It may be shown that for plane electrodes, for any gap length in excess of a certain length which is very small for air at atmospheric pressures, there exists a critical gradient such that any initial ionization, however small, will be so greatly multiplied by ionization by collision that the uniformity of the electrostatic field will be disturbed and the gap broken down. This gradient may properly be called the breakdown gradient of the gap.

Now, there are two requirements necessary if the gap is always to break down at this gradient. First, there must be some initial ionization, for otherwise there would be nothing to start the ionization by collision process when the breakdown gradient is applied. This initial ionization in practical spark gaps is produced by ultra-violet light and penetrating radiations which exist normally in the atmosphere. If this initial ionization is reduced to a very small amount by enclosing the gap in a dark chamber for the time for the ionization to build up sufficiently to unbalance the electrostatic field may become quite large. Thus, Townsend in his "Conduction in Gases" states that for a gap enclosed in a dark chamber a voltage in excess of the normal breakdown voltage may be applied for several seconds before breakdown occurs. Hence, under these conditions, a gap tested under rapidly increasing voltage would show erratic breakdown values.

The other requirement for uniform breakdown properties is that the initial ionization must not be too great. For then even with fields too weak to normally produce a great multiplication of ionization by collision, the space charges developed by the initial ionization may so greatly distort the electrostatic field as to produce an excessive gradient in some portion of the gap, and in this portion a rapid multiplication of ions by collisions may occur. Thus we all know that if a gap is so situated that the ionized vapors from a nearby arc reach it, the breakdown voltages become erratic with abnormally low values.

Ordinarily there will not be a high density of ionization in air because of the high mobility of the ions. They rapidly diffuse away from the spot where they were generated, and are quickly lost by recombinations between the positive and negative ions. Hence an airgap may be given successive tests with fairly short intervals and still not show any progressive weakening.

We do not know whether all these considerations can be carried over to a liquid dielectric like oil but it seems very likely. Some recent work of German physicists showing that ultra violet light increases the conductivity of ordinary insulating materials, points fairly definitely to an ionization process. In any case, if the mechanism of breakdown in oil is at all similar to that of air, we can very readily see why the breakdown of oil should be more erratic. For the ions in oil must have a very low mobility, partly because of the very great viscosity of the medium in which they move, and partly because of the great tendency for polymerization in liquids, so that the individual ions consist of slow moving large groups of molecules. Hence the rate of diffusion must be very slow, so that it is possible to have spots of high ion density and spots of low ion density, with only feeble equalizing tendencies.

Ionization may also persist for a long time because of the slowness with which positive ions and negative ions will meet and neutralize each other. Hence, any slight ionizing agent will produce a relatively large density of ions because this will be determined by the equilibrium when as many ions are lost by recombination as are being generated by the ionizing agent.

The feebleness of the forces tending to make uniform and small the initial density of ionization are quite enough to explain why the breakdown of a small oil-gap is erratic. Add still further the turbulence of the oil under stress, which may at any moment in a haphazard fashion sweep a highly ionized portion of oil into the gap, and the wideness of the probability curves obtained by Messrs. Hayden and Eddy are no longer to be wondered at.

The point which I wish to bring out in this discussion is that there may be no fundamental difference between the mechanism of breakdown of an air gap and an oil gap. The apparent difference is one of degree only and due to the high mobility of particles in air. If air gaps were tested with voltages applied for very short times, say fractions of a micro-second, the results would probably be as variable as those obtained for the oil gap and conversely, if the oil gaps were tested by the application of continuous voltages for very long times, say hours, quite uniform results should be expected.

An Analytical Investigation of the Causes of Flashing of Synchronous Converters

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The object of this paper is to show on what factors the flashing tendency of synchronous converters depends, and how, on the broadest considerations, an improvement of their momentary overload characteristics can be obtained. From the interpretation of a number of oscillograms, and other experimental data, it is shown that a heavy load surge produces unbalanced armature reactions, resulting in abnormal voltage conditions on the commutation, which are in turn largely responsible for the flash. Synchronous stability, stability of commutating conditions, and means of choking down the flash, are the means enumerated by which the momentary overload capacity may be increased.

During the past few years, a noteworthy effort has been made to improve the flashing and the momentary overload characteristics of 60-cycle, 600-volt synchronous converters for railway service. This important work has covered a number of different phases of the problem and has been carried on by the various organizations keenly interested in its success. Some of these phases have been covered by articles and papers published from time to time, describing modifications of design and new methods of protection, while some of the less recent papers explain clearly the very difficult design limitations existing in this type of machine. This literature is referred to in a limited bibliography appended hereto. In the present paper, however, it is intended to deal solely with the processes through which, as a chain of cause and effect, a primary cause leads up to a flash at the commutator. It is particularly important to have a knowledge of this, both to determine effective means of protection and to interpret the varied results of tests.

Flash on a 500-kw. 60-Cycle Converter

There has been a tendency, it is thought, to consider the momentary overload capacity of a converter in too nearly the same terms as that of a direct-current generator. Actually the conditions existing in the two types of machines may be widely different from each other. So long as the converter is operating under steady loads these differences may not be greatly apparent because the alternating and direct currents bear a practically constant relation to each other, and, since they may be considered to flow in opposite directions, the reactive effect is small—less than in any other machine except a fully compensated direct-current generator or motor. The type of overload which is dangerous to the operation of a converter is one which comes on as a heavy surge considerably above the overload setting of the circuit breaker protecting the machine and is consequently relieved in a sudden interruption after a sufficient period has elapsed to permit the circuit breaker to operate. In these circumstances, the internal balance of currents will be severely upset by transfers taking place between the energy of the rotating masses and the energy being converted directly in the armature; resulting in abnormal commutating conditions conducive to flashing. This action then becomes a factor in the overload limitation of the converter. On the other hand, in the case of a direct-current generator the same condition cannot occur; there is but one current in the armature windings and consequently it makes little or no difference whether the input energy is supplied from an external source—a synchronous motor for example—or from the stored energy of its rotating armature.

When a load is applied to a converter, there is a slight momentary drop in speed which results in a permanent phase displacement of the armature behind its position when running light; the displacement being, within certain limits, proportional to the load applied. This action is common to all synchronous machines and is produced by the combined effect of armature reactances and armature reaction. Although the algebraic sum of the alternating-current and the direct-current armature m. m. fs. when summed up over a pole-pitch may be shown to be roughly zero, a study of Fig. 1 will show that in particular points one may be in excess of the other. The direct-current m. m. f. is greater under the interpolar space where the reluctance is high, and the alternating-current m. m. f. under the main pole where the reluctance is much

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lower. It thus happens that the alternating-current part of the resultant m. m. f. is the greater in its influence for reaction than the direct-current part. In addition to this, the resultant direct-current m. m. f. in the commutating zone is neutralized, or even reversed, by the excitation of the commutating-pole winding. The total effect is an appreciable alternating current, or motor reaction, which distorts the main flux backward. The distortion is, naturally, much less than in a synchronous motor, but that it is quite perceptible is shown by Fig. 2, which is an actual field form measurement of a 300-kw. 25-cycle converter. It will be evident that the voltage generated between diametrical rings is no longer a maximum at the instant when the tap-coils pass beneath the direct-current brushes, but at a position on the commutator slightly to the rear, or in the direction against rotation. This point corresponds roughly to the phase displacement.

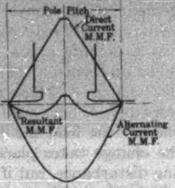

FIG. 1—ARMATURE M. M. F. DIAGRAM FOR A SYNCHRONOUS CONVERTER

In order to obtain direct quantitative measurements of this phase displacement, an oscillographic method was developed by which the internal phase relations could be determined. Briefly, the method consisted in recording two voltage waves; one, the voltage applied across two collector rings, and the other, the voltage of an auxiliary machine rigidly connected to the converter armature. The voltage of the auxiliary machine corresponds to a voltage generated by the field winding of the converter alone, without any reactive effects and, therefore, the relative phase positions of the two recording voltage waves may be used to indicate the phase displacement of the converter armature. A very pronounced advantage of such a method is that it may be used for both stable and transient conditions of operation.

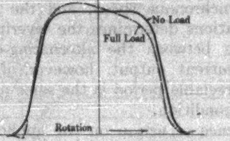

FIG. 2—CONVERTER FIELD FORMS

The phase displacements under various conditions of load were measured on a 500-kw., 60-cycle, 600-volt converter which was used extensively in all the work which these notes cover. It was not used exclusively, however, and the data obtained on it were supplemented to a considerable extent with more from larger machines. The phase displacement results of the 500-kw. converter are shown in Fig. 3. Under stable conditions of load, the results for beyond two and one-half times the rated load, unfortunately, had to be discarded because a sufficient power supply could not be maintained to give steady values. The initial displacement of about one degree is due to the no-load losses of the converter and is, incidentally, purely the action of a synchronous motor. The full-load displacement of six electrical degrees is, as has already been stated, much less than for a corresponding synchronous motor—perhaps only one-fourth of it. To proceed with such a comparison, a synchronous motor may be expected to drop out of synchronism at perhaps 2½ times its normal load; whereas a converter will stand very much more, at least ten to twelve times its normal load in the converter referred to, while it may be argued that a mathematically ideal converter would never drop out of step for the reason that as the displacement approaches 90 degrees, the voltage across the direct-current brushes would approach zero while the synchronizing torque approaches a maximum[1]. For practical converters

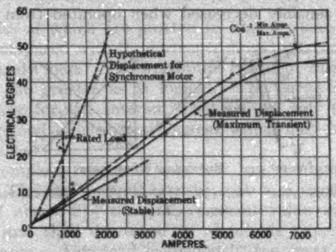

FIG. 3—RELATIONS BETWEEN LOAD CURRENT AND ARMATURE PHASE DISPLACEMENT ON A 500-KW., 600-VOLT, 60-CYCLE CONVERTER

however, high internal losses and flashing will occur before this condition is reached, so that the actual torque will be largely independent of the output and will cause the converter to pull out of synchronism. The tests seem to indicate the displacement may reach a maximum value of 45 electrical degrees before trouble from flashing results.

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[1] When a synchronous machine connected to a source of constant voltage is placed under load, its rotor is angularly displaced by an amount depending upon the impedance drop in both the intervening circuit and in the machine itself. This displacement is a measure of the stability of the machine; the greater the displacement the less the stability. In a simple diagram, such as Fig. 4, where the resistance drop is neglected, it can be shown that the power flow is proportional to the area between the vectors E_g and E_{g1} and as this varies with the size of the included angle it will be consequently a maximum when the vectors are at right angles, as shown in the second diagram. In other words, this latter condition marks the limit of stable operation and beyond this point the machine will pull out of step. This limitation applies not only to the synchronous machinery but to combinations involving synchronous machinery transformers and transmission lines, etc.

It is, of course, to be understood that the value of phase displacement of other converters under normal load is not necessarily the six degrees cited above. This quantity depends upon the design of the particular machine involved. The stability of the converter used in these tests is appreciably greater than what is found in machines of larger ratings. It would be expected, and is a fact, that many machines have a considerably larger displacement at their rated loads.

A factor of considerable importance in the determination of the overload capacity of a converter is the characteristics of the circuit supplying the power. The stability of a synchronous motor, for instance, will be sensibly decreased when operated from a circuit of high reactance and the same thing is true of a converter, but to a greater degree because the small reactive effect of the converter itself forms a smaller fraction of the whole; and, conversely, the external reactance will form a *greater* fraction of the whole. For railway substation installations, where it is usual to install transformers with 15 per cent reactance, it will be expected that stability of the converter will be somewhat reduced. To be exact, the above value of reactance is not maintained on heavy overloads, due to the saturation of the leakage paths, but it will be relatively high to the point where the converter drops out of synchronism. Fig. 4 shows this effect quantitatively with very rough assumptions. It is assumed that external reactance amounts to a constant value of 17½ per cent while the converter displacement at normal load is six degrees. The second diagram shows that the maximum load which the converter could carry under these conditions would be about five times its rated value. Since the external displacement is relatively greater than the phase displacement of the converter armature it therefore becomes largely responsible for the machine dropping out of synchronism.[1]

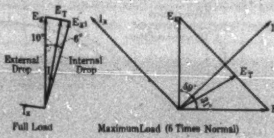

FIG. 4—REACTIVE VOLTAGE DROPS IN A CONVERTER AND SUPPLY LINE

It is to be realized that such a diagram is necessarily very crude and that it can only serve to illustrate a point rather than to give accurate data. Certain factors which have been neglected may however lack the importance which might be given them at first sight. For example, the effect of the series field during such a transient period is not great because any tendency toward sudden changes in flux will be almost completely counteracted by current in the damper winding and shunt field winding for a longer time than it takes the converter to drop out of step. The effect of resistance in the alternating-current circuit will naturally be detrimental although it is usually so small that it is not important except under the heaviest loads.

It follows from the preceding discussion that due to phase displacement in the converter and an additional displacement in any external reactance, the armature takes up a definite phase position for each value of load applied and when a change of load occurs the armature must change its phase position to correspond, moving forward or backward (relatively), depending upon whether the load has been increased or decreased. If the change takes place gradually there will be no resulting disturbance, but if the load changes suddenly the internal balance of currents and reactions will be upset until such time as the armature will have settled into its stable position. When the armature drops back, it delivers a portion of its rotational energy as output at the direct-current brushes which is in addition to the alternating-current input; when it moved forward, extra alternating-current power is required to accelerate it. In consequence of these actions, there is no set instantaneous relation between the alternating-current input and the direct-current output for a transient condition of load, for it will be modified by the rate and direction of energy transfer in the rotating masses.

Hunting is the condition existing when the changes of displacement become oscillatory. In this case, the energy stored in the armature may be taken as fluctuating about a mean value represented by the energy at synchronous speed, and the magnitude of these fluctuations determines the severity of hunting. The relation between the alternating-current input and direct-current output, however, if summed up over an appreciable period is the same as that for the steady load condition.

The sequence of action on the application of load to a converter may be stated in somewhat the following manner: On the closing of the direct-current circuit, the current rises following the ordinary exponential law, being limited at the first instant by only the total inductance of the circuit. The rate of power increase during this period may be high, necessitating a correspondingly high rate of change of armature displacement. If the converter does not fall out of synchronism, the total displacement will be limited to a maximum of less than 90 electrical degrees (see Note 1), but the time in which this movement takes place may be so short that the energy will be given up at a rate comparable to the coincidental output which means that the converter will absorb a considerable part of the shock of the sudden load change and prevent it from passing into the alternating-current system. This cushioning effect may be achieved in severe cases, however, only at the expense of a flash. Fig. 5 is an oscillogram taken to show the effect of the application and interruption of a heavy load on the 500-kw. converter. The alternating-current wave may be taken as a rough measure of the power input. The alternating current, it may be noted, rises at about one-half the rate of the direct current, and reaches a maximum value only after the direct current has begun to decrease. It eventually exceeds the corresponding value of direct current, which shows that the armature has begun to oscillate freely—that is, to hunt. This effect is much more noticeable after the circuit breaker opens, when the indications of hunting are unmistakable. It is of interest to note that the point of minimum alternating-current input occurs about two cycles after the direct current has been completely interrupted, while at the point at which the direct current reaches zero the power required to accelerate the rotor is scaled at about double the rated input of the converter.

FIG. 5—APPLICATION AND INTERRUPTION OF A LOAD ON A 500-KW. CONVERTER

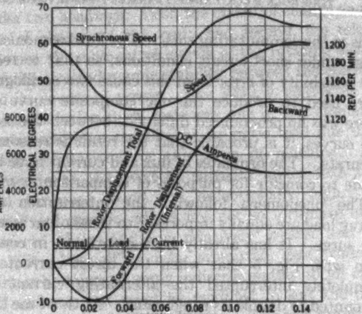

FIG. 6—TRANSIENT RELATIONS OF SPEED AND DISPLACEMENT IN A 500-KW., 60-CYCLE CONVERTER

This brief analysis gives a general idea of the power fluctuations under such circumstances; but, while very interesting, it fails to give a quantitative measurement of the displacement angles involved. To obtain these data, a series of tests was made while loads of various magnitudes were thrown on the converter, the results of which are plotted in Fig. 3 where they can be compared with the corresponding displacements under steady load. The maximum transient displacement is the greater as is logical. The curve shows a tendency for the internal displacement not to increase beyond 45 electrical degrees which may be the actual case.

The complete results of one test are combined in Fig. 6. The short-circuit current rose to a maximum value of about 9½ times the normal value in 0.08 second, and then decreased to about six times full-load current. This load is obviously too great to be maintained by the converter, but, if this had been possible, the final and stable value would have been between these two, though considerably nearer the lower one. The maximum angle of internal phase displacement recorded was 43 degrees which occurred roughly at the instant of minimum current. This is again indicative of oscillatory action. A distinction is made between total displacement and internal displacement; the former term applies to the amount by which the converter drops back into phase position behind the source of power, and thus is the result of the entire reactive drop between that source of power and the armature as well as that in the converter itself. It is this quantity which determines the amount of rotational energy given up by the rotating parts. The internal displacement includes only that which is produced within the converter due to the effective armature reaction and reactance. One point which is worthy of note, and which came as a surprise, is the fact that the initial *internal* displacement is forward instead of backward as might be expected. This simply means that the external displacement due to line reactance, etc., increases faster than the armature can initially drop back. The total displacement is, of course, always backward. This short-circuit test approached the limit of severity which could be thrown on the converter without having it drop out of synchronism. An indication of this is the fact that the total displacement reached a value of 70 electrical degrees. As a matter of fact, it was only the very low value of external reactance which explains why the converter remained in synchronism at all at such a load.

It might be noted in passing that the decrease of load current after the maximum value is reached is closely associated with the phenomenon of phase displacement; and, incidentally, the relation between the two was at first made use of to obtain quantitative measurements of internal displacement. With a constant sinusoidal voltage applied to the rings, the voltage across the direct-current brushes will drop with the cosine of the angle of displacement. If the load current were assumed to drop off also according to this same law, then the ratio of the current at the first dip to the maximum value will represent the internal displacement. That this assumption is more or less justified may be drawn from the comparison of curves of Fig. 3. In the case of another machine the agreement might not be so close, although the method ought to serve at least as a means of comparison between different tests on the same machine.

The magnitude of the energy fluctuations in the converter during short circuits can be estimated from the inertia of its rotating masses and the data of Fig. 6. In this particular case, the energy given up by the armature in the first 0.04 second was about 30,000 ft-lb., and at a maximum rate of 1250 kw. This is about two and one-half times the rated capacity of the machine and amounts to about 50 per cent of the actual output during this period. These figures, therefore, agree with the conclusions drawn from Fig. 5, and serve to demonstrate the fact that the fluctuations of energy which disturb the balance of the reactors are severe.

These figures may also be used as a means of showing the resultant effect on commutation. Assume that the instantaneous ratio of output to input is 2:1; the m. m. f. acting in the commutating zone instead of being the 10 per cent of Fig. 1 becomes 55 per cent of the full direct-current armature ampere turns and if, as was formerly quite usual, the commutating-pole ampere turns amount to only about 40 per cent of this same value, there will be a negative m. m. f. of 15 per cent to produce a flux in the reverse direction. Under such conditions it would be much better for the converter if the commutating poles were removed.

The obvious way to reduce the amount of trouble from this source is to increase the magnetic strength of the commutating pole in relation to the armature until it becomes comparable to that of a direct-current generator. If this be done, the extra ampere turns under normal operating conditions will be used up in a greatly increased reluctance of the commutating pole, while under load surges they will prevent the commutating-pole flux from becoming greatly decreased (relatively) or reversed. This arrangement has become known as a high-reluctance commutating pole, the reluctance being obtained by placing non-magnetic material (which includes air) in the magnetic circuit of the pole. If the strength be increased to 100 per cent, for instance, the conditions referred to above become as follows: In the case of stable operation, 10 per cent of the total m. m. f. is utilized in neutralizing the resultant m. m. f. of the armature and the remaining 90 per cent in overcoming the reluctance of the magnetic circuit. In the case of the assumed surge, 55 per cent neutralizing m. m. f. is required, leaving 45 per cent to produce the commutating flux which means that the latter will be one-half of what it would be under the corresponding stable condition.

These rough calculations have been verified experimentally, using the same converter as in the former tests furnished with high-reluctance commutating poles of approximately 100 per cent strength. The data obtained are plotted in Fig. 7. The flux changes were recorded by an oscillograph connected to search coils in the commutating zone. The flux harmonics are large under short-circuit conditions, so that to reduce the possibility of error from this cause two oscillograms were used to produce the one composite curve. As there was no pronounced difference between the separate curves, it is probable that the result is reasonably accurate. The ordinates of flux and current have been made to coincide for purposes of comparison.

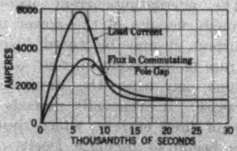

FIG. 7—RELATIONS BETWEEN LOAD CURRENT AND COMMUTATING-POLE FLUX UNDER TRANSIENT CONDITIONS

The phenomena following the interruption of a heavy load are equally important to those of an increasing surge. It has already been mentioned in connection with Fig. 5 that when the direct current was completely interrupted the alternating current still amounted to double its rated value At this time there were no other m. m. fs. acting in the commutating zone, and the only obstruction to the passage of flux was the reluctance of the magnetic circuit. The condition corresponds to a strongly over-compensating commutating pole[2] and tends to occur on all occasions when the load is suddenly reduced.

In Fig. 7, the period intervening between 0.01 to 0.02 second is one of over-compensation due to the sudden operation of the circuit breaker. The excess here is not great for the armature was never displaced to any great extent, and therefore required little accelerating current.

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[2] The alternating-current m. m. f. of the armature acts in the same direction as the m. m. f. of the commutating-pole series winding.

Referring again to the results of Fig. 5, it is possible to make a rough estimate of the flux produced by the unbalanced armature current at the interruption of the direct-current circuit on the same basis as those already made. Assuming then the alternating current to be double the rated value and a commutating pole of 40 per cent of armature strength, the commutating flux will tend to increase to a maximum value of between five and six times that at normal load and will, naturally, generate high voltages under the brush. If a high-reluctance commutating pole of 100 per cent strength is supplied to the converter, the corresponding flux will tend to be only about double the normal value at full load. The pronounced advantage of the high-reluctance commutating pole for the condition of quickly decreasing loads is, therefore, also evident. It might be remarked parenthetically that there is a practical limit to which the increase of reluctance of the commutating pole may be carried. This comprises only one of the possible paths for the flux (others being slot leakage etc.), so that when the reluctance of the commutating-pole circuit become relatively high compared to that of the other paths, the practical limit is reached. The constructional difficulties, of course, increase with the reluctance.

The amount of energy unbalance under transient conditions of load is a measure of the combined effect of several factors which may be conveniently grouped under two headings: First, the extent of change and the rate of change of the load; and second, the relation between the moment of inertia of the rotating element and the electrodynamic stability between the converter and its source of power. The 500-kw. converter used particularly for these tests was one of low moment of inertia and high stability at its rated load due to the design limitations for this type of machine. As a consequence, the overload capacity under both stable and transient loads was exceptionally high. Converters of greater ratings are not so fortunate in this respect; their inertia is relatively greater and their stability less. The data submitted here, therefore, cannot be taken to apply indiscriminately to all classes of machines but must be modified to suit the design proportions for individual cases. The test represented by Fig. 6 for instance, showed that the 500-kw. converter used will carry 9½ times its rated load without dropping out of step or flashing. This cannot be considered a representative figure, by any means, for converters in general, and in addition to this the same converter when operated from high-reactance transformers would not have this overload capacity.

Up to the present point, the converter has been dealt with as a piece of synchronous apparatus entirely, particular attention having been paid to the character of reactions resulting from transient load conditions. The phenomenon of flashing itself is a characteristic of commutating machinery; therefore to show the relation between these reactions and the flashing which may result the converter must be dealt with as a commutating machine. From a careful examination of the available data in the form of oscillograms, high-speed photographs, etc., the immediate causes leading up to a flash-over were ascertained to be in the majority of cases as follows: Sparking under the brushes occurs with heavy overloads in all commutating machinery and is due partly to the heavy currents flowing across the brush contact surfaces, but more to the imperfect compensation of inductive voltages generated in the short-circuit coils effected by the excitation of the commutating pole. Sparking will naturally precede a flash, even though perhaps only for a few thousandths of a second. It produces ionization of the atmosphere at the surface of the commutator which decreases the ability of the converter to resist the first formation of an arc. In nearly every case capable of investigation, the flash developed through the sparking at the brushes being drawn out as the commutator bars receded from the brush until the arc extended through an entire pole-pitch. When this occurs and the arc is between brush arms of opposite polarity, or between brush arm and ground, the flash may be considered completely developed. Experience with electric welding has shown that 20 volts are sufficient to maintain an arc, and although conditions are somewhat different on the commutator, the presence of ionized gases due to sparking is favorable to the initiation of an arc, and the above voltage or probably a higher value indicates the magnitude necessary for flashing. If the above conclusions be generally correct, it means that the voltage conditions and distribution over the commutator, in particular directly ahead of the brushes, *i. e.*, in the direction of rotation, are critical for the propagation of an arc and the development of a flash.

It has been generally appreciated that a converter is far more liable to flash on the opening of the circuit breaker than at the point of maximum current. An investigation of the voltage distribution over the commutator under the two conditions—that of increasing loads, and that of decreasing loads—gives the explanation for this. Take the case of a non-commutating-pole, direct-current machine; here, when loaded, the neutral shifts forward for a generator, and backward for a motor, as is evidenced by the necessity for the shifting of the brushes. In the case of the converter when hunting takes place, very much the same thing is true; the fluctuations of energy in the rotating element represent unbalanced motor or generator reactions and the neutral swings backward or forward of the brush as the machine oscillates in phase position. This effect is plainly observable from the sparking under the brushes which will rise and subside with each oscillation. When the generator reaction is in excess and the neutral is ahead of the brushes, the voltage between a brush and a receding bar is of opposite polarity from normal until the bar is somewhat past the neutral. It is evident that there is no voltage between the brush holder and the commutator capable of propagating an arc forward until after the bar has reached a point where the voltage has risen to an appreciable value in a positive direction, and as this point may be an inch or more from the brush on the commutator surface, the conditions are very unfavorable for production of a flash.

In the case of an excess motor reaction, the neutral has moved backward and the bar, on passing the brush, is moving into a field of steadily increasing intensity, and the voltage gradient over the commutator directly in front of the brush may be much higher than it normally is. A critical voltage, which is readily able to carry the arc forward to the next brush arm, may exist on the commutator almost at the brush itself, and thus the danger of flashing is imminent.

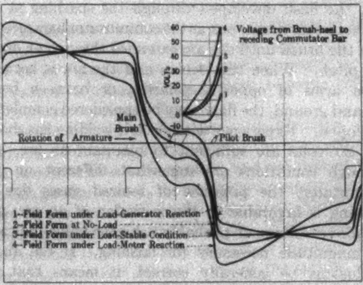

FIG. 8—FIELD FORMS AND VOLTAGE CONDITIONS FOR VARIOUS TYPES OF LOAD

To present this condition in a more definite manner, Fig. 8, which gives several calculated field forms of a converter, has been included. The field forms are drawn up for four different conditions of load, which are, referring to the numbers on the curves: (2) at no-load, (3) under a stable load condition, (4) under load with excess motor reaction, (1) under load with excess generator reaction. The same output has been assumed in each of these last three cases to allow direct comparison; the difference of field form being produced, therefore, by the transfers of rotational energy causing unbalanced reactions.

The changes of flux in the commutating zone between the conditions (1), (3) and (4) are quite marked, although the flux for proper compensation should be the same in each case. The corresponding shifts of the neutral are equally pronounced. If, for instance, the converter were hunting with sufficient severity to produce the unbalanced reactions of this figure, the neutral would swing between the two extremes (1) and (4) with each oscillation.

The inset voltage curves refer to the voltage difference between the heel of a brush and a commutator bar, as it moves forward. They represent in a way the relative tendencies toward flashing for the conditions of operation assumed. At no-load this voltage at the point marked "pilot-brush" is given as 12 volts, which corresponds to that actually measured on the converter. Under the stable load, this voltage is increased only slightly. The same load, while increasing, produces a voltage of − 3 volts at this point, and while decreasing + 30 volts. The significance of these voltages may be inferred from the consideration that if 25 volts are required to maintain an arc on the commutator, in the former case no such voltage will exist on the commutator until the bar has receded a considerable distance from the brush, and it is unlikely that an arc will be propagated forward. In the latter case, a critical voltage may exist almost at the heel of the brush, and the conditions are entirely in favor of the propagation of a flash. It may be said, therefore, that during a period of increasing load a converter is in a sense self-protecting against a serious flash; but that when a load is suddenly decreased, as when a circuit breaker opens, a flash is much more likely to occur, a conclusion thoroughly borne out by experience.

In order to obtain some direct information on this particular action, a number of short-circuit tests was made on the converter having a small pilot-brush located on the commutator at the point indicated in Fig. 8. By this means, the voltages in the commutating zone, critical from the standpoint of flashing, were measured under various transient conditions and the results form a striking confirmation of the theory outlined above. In Fig. 5, the upper line is a record of this voltage. Before the application of the short circuit this "pilot-brush voltage" was about 12 volts, but during the sudden increase of load it dropped slightly below zero, meaning that the neutral had swung forward. Under the steady load condition, it rose to nearly 50 volts above zero, indicating that the neutral was permanently displaced backward. At the opening of the circuit breaker, the voltage exceeded 100, indicating that the decreasing load forced the neutral backward although the armature itself was being accelerated forward. Unfortunately, the oscillogram ended just as a period of free oscillation was beginning, although the commencement of the characteristic indications are evident.

Fig. 9 is a somewhat similar oscillogram but taken during a much heavier short circuit. The current reached a value of 9750 amperes or about 11½ times normal value and the effects are, therefore, sufficiently pronounced to repay a rather detailed study, through which a relatively complete history of the internal actions during the test may be traced. The negative pilot-brush voltage indicates the release of stored rotational energy as in Fig. 5, but at a higher rate for the voltage here drops to 80-90 volts. This is sufficient to convert the sparking at the brushes into a flash which is indicated by the dip in the current wave. However, as the position of the neutral was far forward, the flash was not propagated to the next brush arm and it existed more in the form of a momentary "spit" of considerable severity. As the neutral receded backward with the increase of phase displacement, the voltage initiating the flash decreased to a point where this flash stopped entirely (where the current dip ends). The transition to the stable condition was never completed in this phase of the test, for the circuit breaker opened while the armature was still moving backward. At the interruption of the direct-current circuit, the pilot-brush voltage rose immediately to a maximum value of perhaps 120 volts, which represents a greatly aggravated case of (4) of Fig. 8. At this point the converter flashed the second time but with the reversed voltage conditions on the commutator and as there was nothing to stay the progress of the flash, it progressed completely to the next brush arm where it would have developed seriously had it not been for flash guards supplied to the forward side of the brush holders which isolated the arc on the moving surface of the commutator. This effect greatly limited the severity of the flash and choked down the amount of power expended, so that the armature was allowed to move forward in phase displacement. Thereupon, the unbalanced reaction dropped in value and the neutral approached its normal position again. This proceeding cut off the means whereby the flash was continually being propagated forward and the arc naturally died out. The beginning of the regular descent of the pilot-brush voltage, in Fig. 9, indicates the cessation of flashing. This second flash was of rather short duration as well as the first. If the flash had reached some unguarded point of opposite potential, as would have been the case without the protection of flash guards, it would have been necessary to shut down the machine to kill the arc and protect it from serious injury.

This test fairly exemplifies the principles advanced in the previous part of this paper. It represents as well, a service of extreme severity and considerably in excess of anything which might reasonably be expected of the converter. To permit this performance, the apparatus used included several special features. The converter itself was furnished with high reluctance commutating poles, such as have already been referred to. Flash-guards were placed on either side of the direct-current brush arms to insulate the brush holders from conducting gases, and a special arrangement of brush-holder cross-connections was used to control the flash to a certain extent. The transformers used were of lower reactance to reduce the external impedance to a minimum. The circuit breaker was set for a slightly higher speed than would ordinarily have been considered necessary so that it might operate before the armature had reached its maximum displacement. This was essential to prevent the converter from dropping out of synchronism on extreme momentary overloads. The circuit breaker actually began to open in 0.06 second while the maximum displacement occurred in the neighborhood of 0.08 second. It may be observed that the circuit breaker did not completely open the direct-current circuit in this test; this is because a resistor had been connected across its contacts for previous tests, but there is no particular significance of it in the present connection. This general arrangement, however, tends to reduce the probability of flashing.

FIG. 9—HEAVY SHORT CIRCUIT ON A 500-KW. CONVERTER

This short-circuit test did no injury to the converter beyond a certain amount of erosion of the brush surfaces caused by the heavy load current and circulating current in the brushes. The machine was not shut down and it was found practicable to place it under load again immediately, although not to its full rated capacity until the brush surface conditions had become somewhat improved.

Two more tests taken under a different condition will be referred to. For these tests, the converter was protected by a high-speed circuit breaker by which is meant one which will completely operate within 0.01 of a second. Fig. 7, although not quite typical on account of the time of operation being slow, shows the characteristic current curve very plainly. By making a comparison between this figure and Fig. 6

on a time basis, it may be noted that the initial rates of current rise are not widely different so that the displacements for the two tests may be assumed to correspond with the same accuracy. With the current limited to a time of 0.006 or 0.007 of a second the resulting displacement must be very small; and in fact the internal displacement of the converter will be forward, as has been independently verified. In order that an idea may be gained of the transient phenomena involved Fig. 10 is referred to. The test shown here duplicates that of Fig. 7 except that different quantities were recorded. The fluctuations of both alternating current and of the pilot-brush voltage are so small that it is evident that the great speed of the circuit breaker forestalls any pronounced internal disturbance. Both of these tests represent dead short circuits thrown on the converter, demonstrating that complete protection may be obtained in this manner. Fig. 11 is reproduced from a photograph taken during one of these tests.

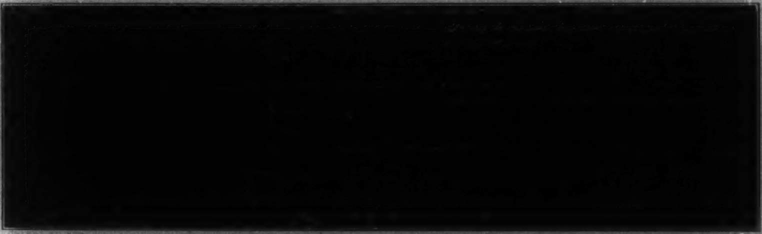

FIG. 10—ACTION OF A HIGH-SPEED CIRCUIT BREAKER

FIG. 11—DEAD SHORT CIRCUIT ON A 500-KW. CONVERTER PORTECTED BY A HIGH-SPEED CIRCUIT BREAKER. (SEE FIG. 10.)

Fig. 12 is from a multi-exposure photograph taken with a high-speed camera[3] to study the development of a flash on the commutator. To compress the phenomenon within the limited time, the high-speed circuit breaker was used with certain modifications to permit the formation of a flash. The exposures are numbered consecutively 1, 2, 3, etc. and are taken 0.001 of a second apart. From comparing these exposures with the oscillogram taken on the same occasion, exposure No. 6 is found to occur at the instant of maximum current, which was 8200 amperes. Up to this point, it may be noted that the flash did not develop beyond the category of a severe spit; at the sudden opening of the circuit breaker, however, the following exposures 7, 8 and 9 show sudden expansion forward of the flash which takes place at even a faster rate than the motion of the commutator itself. These photographs, which record the actual state and confines of a flash at successive intervals over a period of rise and decay of load current, form an important support to the conclusions regarding the propagation of an arc under these two conditions, as set forth in some of the foregoing paragraphs.

FIG. 12—DEVELOPMENT OF A FLASH ON THE COMMUTATOR

The principles set forth in this paper showing the very intimate connection between the synchronous action of a converter and the flashing at the commutator are the outcome of a series of tests extending over several years and a careful analysis of all available data whether derived from these tests or from other sources. It is believed that the conclusions are substantially correct and that they can be used to cover other similar phases of the problem not mentioned here. By applying these principles to the problem of increasing the momentary overload capacity of converters, the following main lines of progress are suggested:

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[3] J. Legg. The Polar Multi-Exposure High-Speed Camera, *Electric Journal*, December, 1919.

(1) The improvement of synchronous characteristics of the converter installation to obtain high stability and the reduction of the moment of inertia of the rotating masses of the converter.

(2) The reduction of the effectiveness of the unbalanced reactions in producing high voltages in the commutating zone. (High-reluctance commutating poles are an instance of this).

(3) The prevention of the complete propagation or culmination of the arc by the insulation of conducting parts around the commutator by means of flash-guards and other devices.

(4) The limitation, by external means, of the maximum severity of the surges thrown on the machine. (In which might be included the high-speed circuit breaker).

These principles have been utilized in devising suitable means of improving the characteristics of commercial types of 60-cycle railway synchronous converters with the result that they have proved themselves much superior to their predecessors.

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Discussion

J. L. Burnham: I would like to discuss the paper in the reverse order from which it is given. To show the relation of Mr. Shand's paper to previous discussions on this subject, a brief review of the bibliography he has appended seems desirable. In 1910 Messrs. Lamme and Newbury presented a paper on the use of commutating poles in synchronous converters in which they implied doubt of their usefulness. Their reasons, broadly stated, were:

Pulsation in the armature reaction and disturbances of the normal relation between alternating and direct current with quick changes in load, which caused wide variations in the resultant commutating field excitation for a given load. The phenomena discussed in Mr. Shand's paper were qualitatively stated at that time and since have been enlarged upon by others. Mr. Shand now gives a more definite picture of what occurs during sudden changes in load and short circuits.

In the discussion of Messrs. Lamme and Newbury's paper I gave results of tests on 25-cycle, 1200-volt converter with a large air gap for the commutating pole which gave decided improvement in performance for heavy loads thrown on and off. Since that time it has been the practise to use large air gaps for commutating poles of 25-cycle synchronous converters. For 60-cycle railway converters the large air gap was not sufficient to give the desired performance. The effect has been increased in the development of high reluctance commutating poles.

In 1914 Mr. Yardley presented a paper on the use of reactance for protection of synchronous converters. The results obtained did not seem encouraging and reasons were presented in the discussion at that time showing the inherent difficulties that would be introduced by the use of reactance, particularly in the a-c. circuit. These reasons are further emphasized in Mr. Shand's paper.

Recognizing these inherent characteristics of converters we began work to devise means for eliminating the effects with the view of avoiding damage to the machine and minimizing interruptions to service. Two lines of investigations were followed.

First: To take care of the flash so it would not spread and would be stopped when the short circuit was removed and

Second: To prevent formation of the arc.

The first line of investigation resulted in the development of flash barriers and the second in the high speed breaker. A paper presented at the annual convention in 1918 by Messrs. Linebaugh and Burnham described the investigations and the devices then 'developed. At that time we made the first claim for complete protection of a converter against any disturbances in both a-c. and d-c. systems, that would give interruptions to service no longer than ordinarily resulting from moderate overloads that would trip the main circuit breaker.

In 1919 a line of high reluctance commutating pole 60-cycle railway converters was developed and also a new type of protected brush rigging was introduced to give greater clear distance between brush holders of opposite polarity. The high reluctance poles increased decidedly the amount of disturbance that the machines would stand without flashing and the new type of brush rigging gave much less opportunity for the arc to spread and do damage. These improvements made the 60-cycle railway converter much better for average service when protected with the usual devices.

The next year, 1920, Mr. M. W. Smith presented a paper on "Suggested Remedies for Flashing of 60-Cycle Converters" which reviewed some of the phenomena involved and described tests made on the so-called flash suppressor and protected brush rigging. Tests indicate that under very delicately adjusted conditions some protection would be afforded but at that time the scheme was not considered commercially useful. I assume that this is still the status of this line of investigation.

Regarding Mr. Shand's conclusions suggesting main lines of progress: No 1 is well recognized and I believe has been followed by most designing engineers for a number of years past if for no other reasons than lower costs.

2. High reluctance commutating poles were investigated about 5 years ago and a complete line of 60-cycle, 600-volt converters was developed and standardized in 1919.

3. Experimental work on flash barriers was done 5 to 6 years ago and results were described in a paper presented at the annual convention in 1918 and have since been used for certain difficult service, but principally for automatically controlled machines.

4. The high-speed breaker investigation started about six years ago. At that time there was no information to determine what speed would be required of a d-c. circuit breaker to prevent

flashing on short circuit. I recommended that it be made to open the circuit within ½ cycle for 60 cycles or 1/120 of second, the time in which a commutator bar passes from brushes of one polarity to those of opposite polarity. This was about 20 times faster than existing breakers and seemed a most difficult problem but this speed was attained in some breakers built about 5 years ago, and a new design, much simpler, stronger and cheaper has since been built to give the same high speeds.

To give a better idea of the form of protected rigging and flash barriers, and the performance of machine under short circuit, I wish to show some pictures:

Fig. 1 shows short circuit on a 25-cycle, 1200-volt converter built in 1910. This is the machine on which experiments with large air gaps for the commutating pole were made and which permitted 4 times load to be thrown on and off without any serious disturbance. However, when short-circuited this machine arced over between adjacent sets of brush holders, from brush holders to bearings and even to projecting field connection strips. The amount of damage to the machine was remarkably small, compared to the pyrotechnics and effect on the operators nerves.

Fig. 1—Short Circuit on Type H C 6-750-500-1200 Volt Synchronous Converter

Fig. 2 shows a more modern form of brush rigging assembled on a 500-kw., 60-cycle standard railway machine.

To show more detail of a brush holder bracket, the next picture (Fig. 3) is an end view with the insulating end cover removed. It will be seen that the rigging is completely enclosed by insulating material and that the spring is radially in line with the brush. This type of rigging covers a very narrow portion of the commutator and gives maximum clear space on the commutator over which an arc may be established. This increased the load disturbances that a machine will stand without flashing over but it is not entirely effective in preventing a flashover when short-circuited.

Fig. 4 shows flashover with this sort of rigging, the curretn being interrupted by a breaker of ordinary speed. Such a flash will generally clear itself, as short circuits in service are generally limited by feeder resistance, but occasionally will hang on long enough to trip the a-c. circuit.

Fig. 5 is a 750-volt, 60-cycle converter having the radial type brush rigging and latest type flash barrier.

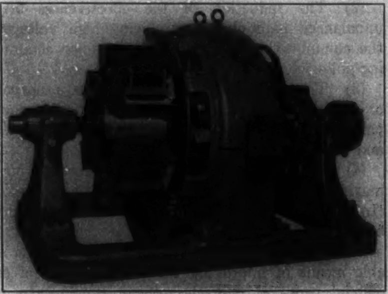

Fig. 2—Type H C C-6-500-1200-600 V C W Synchronous Converter

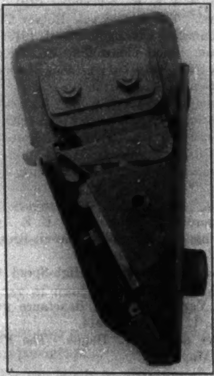

Fig. 3—Radial Brush Holder Unit Outer End Insulation Removed

Fig. 6 is a perspective and cross section of the flash barrier, the action of which is explained as follows: when short circuit occurs the arc is formed between the brushes and the leaving commutator segments, being drawn out in direction of rotation as shown by the arrow and expanding outward. The arc is mechanically scooped from the commutator by the pointed barrier which has metal inserted in its face. This metal and the barrier as a whole has a cooling effect, reducing the arc in volume and directing where it can do no harm by completing any further short-circuit paths. A second and third scoop shaped barrier are also provided as additional factors of safety in case of poor adjustment or defect of the first barrier. It is seldom that the second barrier is ever required to move any of the arc from the commutator. The member at right angles and in front of the first barrier shown more clearly in the perspective splits the arc and confines that portion developed in the front of the two sections in their respective sections so they do not pile up at one corner, thus avoiding the escape of conducting gases under the side member. This form of barrier allows free expansion of gases, by proportioning the expansion chambers with increasing area at increasing distances from the commutator. Furthermore, it being low, releases the gases quickly after changing their course and allows free dissipation in the open air.

As has been previously shown for the radial type of protected brush rigging, it is not sufficient to have the brushes and holders surrounded with the insulating materials. It has been demonstrated that the arc, when formed must be quickly lifted from the commutator or otherwise quickly and definitely disposed of to insure against interruption to service.

Fig. 7 shows a short circuit on two 750-volt, 60-cycle converters in series for 1500 volts, protected by flash barriers and circuit breaker of ordinary speed. The current was approximately 20 times full load. The exposure of the negative was throughout the short-circuit period. It will be seen that the arc is scooped from the commutator by the first barrier and thrown out almost radially where it can do no harm. Sixty-six of these short circuits were applied in succession and no appreciable burning or damage done that would prevent the machine from carrying its usual loads. The photograph is the 46th short circuit and is representative of all. This is probably the most severe short-circuit test ever applied to a commutating machine, the current in each of the 66 tests being about 20 times full load.

Fig. 4

Fig. 8 is a side view looking down into the barrier, showing how the arc is confined to the first expansion chamber following the brushes. It is evident how the arc splitter holds the arc from moving sidewise.

As a-c. disturbances may also cause flashing, barriers are equally useful in such emergencies.

Fig. 9 is a short circuit of the same machine protected with barrier and high-speed breaker, two machines being operated in series at 1500 volts. It will be noticed that the high-speed breaker has so reduced the sparking unit that it is only slightly visible

Fig. 10 shows the 750-volt, 60-cycle converter with flash guard removed after it had been subjected to 50 high-speed short circuits. The commutator, brushes, and barriers were unburned. The only mark indicating that short circuits had occurred were slight soot deposits.

Fig. 5—Radial Unit Type Rigging with Flash Barriers, 300 Kw., 60-Cycle Synchronous Converter

It will be noticed that the barriers have three point supports and may be quickly removed by unscrewing three nuts.

Fig. 11 is a view of 1500-kilowatt, 600-volt, 50-cycle machine with a different type of brush rigging undergoing short circuit with barrier and high-speed breaker protection. The total amount of sparking is completely visible and will be noticed as a small triangular point of light. The barrier was not needed for protection in this case but is presented as a good view to show the construction.

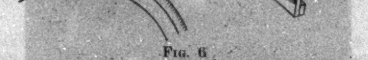

Fig. 6

J. J. Linebaugh: The conditions existing in d-c. generators and synchronous converters under load and short-circuit conditions are radically different, due to the interconnection of the a-c. and d-c. circuits so that commutating conditions are vitally

Fig. 7

affected and different remedies have to be used to produce a good commercial machine.

Figs. 9 and 10 in the paper show very clearly the reason for the flashing of a synchronous converter under rapidly decreasing load, due to opening of the circuit breaker and the great benefit obtained by the use of a high-speed circuit breaker. It is evident that the high-speed breaker removes the cause of the high voltage generated between bars as shown in Fig. 9, due to the fact that the short circuit is prevented from reaching a high value and reduced in a very short interval of time. The resulting ampere second load is so small and of such short duration that it does not cause great enough armature displacement to give sufficient voltage difference to hold an arc when the commutator bars move from one brush holder to the next.

Fig. 8

Fig. 9—Short Circuit on Two H C C 6-300-1200-750 Volts—Two Machines in Series 1500 Volts—Equipped with Flash Barriers. High Speed Breaker Set to Trip at 1400 Amperes. Machines Carrying Normal Load when Short-Circuited

Fig. 10—Type H C C -6-300-1200-750 Volt Synchronous Converters with One Barrier Removed after 50 Short Circuits, Protected by High Speed Breaker

The flash barriers described by Mr. Burnham are designed to take care of just such phenomena as described by Mr. Shand in Figs. 5 and 9, as the resulting arc is wiped off and raised above the commutator and cooled and dissipated so that the continued growth of the arc is suppressed. The long thin path between the barrier and commutator also tends to baffle the arc and the heat is extracted due to the cooling obtained from the barrier. If the arc should persist after the first barrier or hurdle, it has a chance to expand and the operation is repeated. Actual experience indicates that two of these hurdles are sufficient to stop practically any arcing which has been experienced. Tests indicate that a form of barrier such as described, designed to remove the arc quickly from the commutator, is superior to the narrow barrier described by Mr. Shand. These barriers are applied to all machines above 750 volts, as standard practise, in addition to automatic substation machines, and have been very successful in actual operation for several years.

The 60-cycle 750/1500-volt machines shown by Mr. Burnham, have all the improvements in design developed during the last few years and their behavior under test indicates that they are practically equal to the 25-cycle converter in every way.

FIG. 11

Mr. Shand has not covered the effect of operating the rotary converter at poor power factor due to weak or strong shunt fields, and oscillograms similar to Figs. 5 and 9 would be of interest.

One advantage of the barrier, not brought out, is its ability to take care of flashing caused by a-c. disturbances of any kind. The high-speed breaker does not take care of this trouble, but the barrier prevents flashing over from such causes and the combination of the two types of protection as stated in the 1918 paper by Mr. Burnham and the writer, gives absolute protection under all short-circuit conditions.

E. B. Shand: The intention in writing this paper was not so much to set forth any new principles or any radical conclusions as to present the problem of converter flashing from a standpoint which has been in the past, it is felt, somewhat neglected. It has not been entirely neglected, for as Mr. Burnham has stated, most of the facts of the case have been stated at one time or another, but usually without proper correlation and seldom with any adequate experimental substantiation. The author, however, wishes to acknowledge a debt to the results of some unpublished work done by Mr. C. E. Wilson in 1910 under the direction of Mr. B. G. Lamme. This comprised tests and calculations on a converter in short circuit with reference to the inertia energy involved.

With respect to Mr. Burnham's references to the conclusions of my paper, these are not intended to be regarded as being a departure from present practise. All of the principles involved have been well recognized and to find the first developments of any one of them, it would be necessary to go back at least a decade.

The performance of the 750-volt, 60-cycle converters as shown in Fig. 7 of the paper is indeed striking. It is a demonstration of machines immune from destructive flashing under extreme, severe conditions. The result of a dead short-circuit test on the 500-kw. converter referred to in the paper is shown herewith, in Fig. 12. A circuit breaker of the ordinary type was used on this test, but the flash guards used were considerably simpler in form than those described by Mr. Burnham. The condition of the machine was, in fact, practically the same as for Fig. 9 of the paper except that it was completely short-circuited. The current rose to 22 times its normal value, at which point a flash of limited proportions occurred. The machine dropped out of step and later dropped back a second pole into step again. Spitting occurred in both instances, as would be expected, for the condition would be the same as synchronizing with the brushes down after starting. As may be seen from the oscillogram, the flashing was never destructive, and there was no injury done to the machine beyond a slight blackening of the commutator so that there was no reason why the machine might not have been put directly back into service.

FIG. 12

In reference to the function of flash guards, I do not thoroughly agree with their principle of operation as given by Messrs. Burnham and Linebaugh. It is stated that the flash guard accomplishes its results by scooping the flash from the commutator; this may be true to a certain extent but to a greater extent it is the effect of choking off the core of the arc which makes it unstable and breaks it. For instance, Fig. 13, take the case of an arc struck between two electrodes, one electrode projecting through a plate of insulating material. If this electrode be now withdrawn, the arc is confined at one point to the dimensions of the hole, and if this be small enough the attenuation of the arc will quickly break it. When as one of these electrodes a bar passes under a guard, the arc is attenuated in the same manner and broken. (Fig. 14).

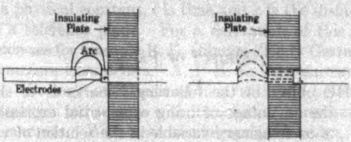

FIG. 13

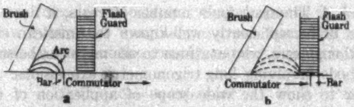

FIG. 14

The Use of Superimposed Imaginary E. M. Fs. Currents, and Fluxes in the Solution of Alternating-Current Problems

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Fellow A. I. E. E.
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Review of the Subject.—*The solution of some advanced problems on alternating currents leads to rather complicated trigonometric transformations. Let now, in addition to the real sinusoidal currents and voltages, certain imaginary currents and voltages be assumed to exist in the same circuit. These imaginary quantities may be selected of such a magnitude and phase that together with the real quantities they will give simpler mathematical expressions than the real quantities alone. In the final results the real and the imaginary terms can be readily separated, because an imaginary voltage cannot produce a real current, and vice versa.*

This method is based on some remarkably simple properties of certain mathematical functions which contain a real and an imaginary term, as compared to the properties of similar functions containing real variables only.

The following two analogs may make this method clearer.

A. In order to make extremely fine platinum wire, a piece of heavier platinum wire is coated with silver and then passed successively through several dies until it is reduced to the smallest practicable size. Then the tubular coating of silver is dissolved in nitric acid. It would not be possible to draw platinum alone to the same size. Here the use of silver is analogous to that of imaginary quantities in alternating currents. Silver is carried along in the operations and separated in the end.

B. In the manufacture of common ether, sulphuric acid is combined with alcohol and carried through certain operations. In the end this sulphuric acid is separated and used over and over again. Sulphuric acid in this case may be likened to imaginary currents and voltages which are added to real quantities at the beginning of the problem and separated in the end.

The immediate occasion for the writing of this article was a paper by Mr. Gilman referred to under (2) in the article. Had Mr. Gilman used superimposed imaginary currents, several pages of tedious mathematical transformations could be saved.

A more general reason for writing this article was a desire to bring this method to the attention of American engineers. It is hardly mentioned in American text-books, while it is quite well-known in England and on the Continent of Europe. As is stated in the introductory paragraph to the article, the method is not new, and the examples quoted are too self-evident to claim any originality. A brief introduction to the method will be found in the author's "Electric Circuit," p. 97.

The importance of the method lies in the possibility of solving certain electrical problems in a shorter and more direct way, and possibly in making the solution of certain problems feasible which in the ordinary way lead to too complicated expressions. It is a mathematical tool, and as such should find its place among other useful mathematical methods used in the solution of physical and engineering problems.

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Problem 3—To express analytically a gliding magnetomotive force due to a symmetrical *n*-phase system. (800 w.)

OBJECT OF PAPER

The object of the following remarks is to show the advantage of using exponential expressions of an imaginary variable in the solution of various problems involving alternating currents. While the method is not new, and has been used by writers like J. J. Thomson for a number of years, it does not seem to be sufficiently well-known to American electrical engineers, who continue to use more cumbersome methods involving long trigonometric expressions. In order to show the wide scope of application of this method, three entirely different problems are solved below, namely:

(1) To find the current in a circuit containing a resistance, a reactance and a capacity in series. The solution is based on the superposition of an imaginary e. m .f. upon the given terminal voltage.

(2) To find the distribution of eddy currents in a rectangular conductor in an armature slot. The problem is solved by superimposing imaginary eddy currents upon the real ones.

(2) To find an expression for a gliding m. m. f. or flux due to a symmetrical *n*-phase system. A simple expression is found by adding imaginary m. m. fs. to the real ones.

GENERAL CONSIDERATIONS

Let an alternating voltage $E \cos w\,t$ be applied to an electric circuit and produce in it certain currents and fluxes (magnetic or electrostatic, or both). The usual theoretical investigation of such a circuit, even without the transient part, is somewhat unwieldy because some terms in the equations contain $\sin w\,t$ while others contain $\cos w\,t$. We shall assume therefore that an addition to the real voltage, $E \cos w\,t$, an imaginary voltage $j\,E \sin w\,t$, acts upon the same cir cuits, where $j = \sqrt{-1}$. The total "complex" voltage is

$$e = E \cos w\,t + j\,E \sin w\,t = E \exp. j\,w\,t \qquad (1)$$

where

Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

$$\exp. j\, w\, t = \epsilon^{jw} \qquad (2)$$[1]

The real part of the voltage $E \exp. j\, w\, t$ reaches its positive maximum at the instants $w\, t = 0$, $w\, t = 2\,,\pi$ etc. The real part of the voltage

$$e = \exp. j\,(w\, t + \gamma) \qquad (1a)$$

reaches its positive maximum at $w\, t = -\gamma$, that is, it leads the first voltage by the angle γ. In practical applications it is sometimes convenient to write the second voltage also in the form $E \exp. j\, w\, t$, only in this case E is no more a real quantity but a complex constan tof the form $E \exp. j\, \gamma$, where angle γ must be given separately. Thus if in equation (**1**), E is understood to be a complex quantity, then the equation represents a system of two equal sinusoidal voltages of the same frequency, a real and an imaginary one, in quadrature with one another. The exponential part of the factor E gives the angle by which this system of two voltages leads a reference system in which the real part reaches its maximum at $t = 0$.

This simplification is of extreme importance because in many cases it allows us to dispense with the longer notation (**1a**) and to use the shorter notation (**1**), no matter what the phase of an alternating quantity might be. The proper phase is included in the complex expression for the amplitude.

A complex voltage (1) produces in the circuit a complex current, the real voltage giving rise to a real current, and the imaginary voltage to an imaginary current. We thus can express the total complex current as

$$i = I \exp. j\, w\, t \qquad (3)$$

where, generally speaking, I is a complex quantity out of phase with the complex voltage E. Expressions (**1**) and (**3**), when used in the equations of a circuit, give simple relationships among its constants *because any derivative or integral of the exponential function, exp. j w t, with respect to t, is equal to the function itself multiplied by a certain constant, and thus the exponential factors drop out of the result.*

1. *A Circuit Containing Resistance r, Inductance L, and Capacity C in Series.* The well-known differential equation of state is

$$L \frac{d\, i}{d\, t} + r\, i + \frac{q}{C} = e \qquad (4)$$

where q is the condenser charge. Differentiating with respect to the time we get

$$L \frac{d^2 i}{d\, t^2} + r \frac{d\, i}{d\, t} + \frac{i}{C} = \frac{d\, e}{d\, t} \qquad (5)$$

Substituting the values of e and i from equations (**1**) and (**3**) in equation (**5**), gives

$$L\, j^2 w^2 I \exp. j\, w\, t + r\, j\, w\, I \exp. j\, w\, t + (I/C) \exp. j\, w\, t = E\, j\, w \exp. j\, w\, t.$$

The factor $\exp. j\, w\, t$ may be canceled on both sides of the equation, and we get

$$I\,[-L\, w^2 + j\, r\, w + I/C] = E\, j\, w.$$

Multiplying both sides by $-j$ and dividing by w this expression is brought to the usual form

$$I\,[r + j\,(L\, w - 1/C\, w)] = E \qquad (6)$$

from which the well-known expressions for the impedance, z, and the phase displacement, ϕ, of the circuit may be derived. Namely, put

$$\left.\begin{aligned} r &= z \cos \phi \\ L\, w - \frac{1}{(C w)} &= z \sin \phi. \end{aligned}\right\} \qquad (7)$$

Equation (**6**) then becomes

$$I\, z \exp. j\, \phi = E \qquad (8)$$

which means that numerically the voltage is equal to the current multiplied by z, and leads the current by the angle ϕ. The whole treatment does not involve the use of the expressions $\sin w\, t$ and $\cos w\, t$ at all.

2. *The non-uniform alternating-current density Δ in an embedded armature conductor of rectangular cross-section* is expressed by the partial differential equation

$$\tfrac{1}{2}\, w \frac{d^2\, \Delta}{d\, x^2} = \alpha^2 \frac{d\, \Delta}{d\, t} \qquad (9)$$

in which $w = 2\,\pi\, f$ has the same meaning as before, α is a physical constant, t is time and x is the distance from a reference plane. For a derivation of this expression see for example R. E. Gilman, "Eddy Currents in Armature Conductors," A. I. E. E. TRANSACTIONS, 1920. We are not concerned here with the proof of this equation but merely with its solution using imaginary currents. With a sinusoidal applied voltage, the current density in each layer $d\, x$ varies according to the sine law with the time, but is different in amplitude and in phase from layer to layer. Superimposing in each layer a quadrature imaginary current upon the real current, we may put the complex current density in the form

$$\Delta = u \exp. j\, w\, t \qquad (10)$$

where u is a complex function of x and takes into account the distribution of the current in the cross-section of the conductor. Substituting the value of Δ from equation (**10**) in equation (**9**) and cancelling the exponential term, we get

$$\frac{d^2\, u}{d\, x^2} = 2\, j\, \alpha^2\, u \qquad (11)$$

This differential equation does not contain time and is much simpler than the original equation (**9**). The well-known solution of equation (**11**) is

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[1] In this article the notation $\exp. j\, w\, t$ is used in place of the usual exponential notation, because the first form is better adapted to the modern mechanical typesetting. While the difference may not be of importance in a mathematical deduction in which exponential terms occur infrequently, it seems preferable to use the straight "lower case" notation in the following problems because the formulas are predominantly of the exponential type and the principal transformations occur in the exponents. We are used to the expression $\log x$ and there is no reason why the inverse function, $\exp. x$, should not be written without using superior letters.

$$u = P \exp. \beta x + Q \exp. (-\beta x) \qquad \textbf{(12)}$$

where P and Q are complex constants of integration, and

$$\beta = (1 + j)\,\alpha = \alpha \sqrt{2j} \qquad \textbf{(13)}$$

Thus, the complex flux density is

$$\Delta = P \exp. (\beta x + j w t) + Q \exp. (-\beta x + j w t) \qquad \textbf{(14)}$$

Separating the real part of this expression from the imaginary, a formula is obtained for the true current density in the conductor, at any instant t and at any point corresponding to the distance x. A perusal of Mr. Gilman's article will readily show the advantage of the above method as compared with the use of long trigonometric expressions which lead to simultaneous equations.

3. *Polyphase Gliding Magnetomotive Force.* It is known to students of polyphase machinery that n *alternating* sinusoidal magnetomotive forces of amplitude M each, differing in time by $2 / \pi\, n$ from each other and shifted in space by $2\pi / n$, produce a uniformly *gliding* magnetomotive force of amplitude $\tfrac{1}{2} n M$. See, for example, E. Arnold, *Wechselstromtechnik,* Vol. III (1912), p. 241. The usual proof may be simplified by superimposing imaginary magnetomotive forces upon the real. To simplify the formulas further we select such a unit of time that one cycle of current takes place in 2π units of time. Then variations of a magnetomotive force with the time are expressed by the factor $\cos t$, because $w = 1$. Similarly we select such a unit of length that a complete wave of magnetomotive force occupies 2π units of length. The variations of the m. m. f. in space are then expressed by the factor $\cos x$. Thus, an instantaneous m. m. f. due to the first phase, at a point x and at an instant t is

$$m' = M \cos t \cos x \qquad \textbf{(15)}$$

We now superimpose upon this m. m. f. an imaginary m. m. f in time quadrature and in space coincidence with it, that is, one of the form $j M \sin t \cos x$. We then get the following *complex* wave:

$$m = M \cos x \exp. j\, t \qquad \textbf{(16)}$$

But according to a well-known formula of trigonometry of complex angles

$$\operatorname{Cos} x = \tfrac{1}{2} [\exp. j\, x + \exp. (-j\, x)] \qquad \textbf{(17)}$$

so that equation (**16**) becomes

$$m = \tfrac{1}{2} M [\exp. j\,(t + x) + \exp. j\,(t - x)] \qquad \textbf{(18)}$$

The factor $\cos (t + x)$ corresponds to a wave gliding synchronously towards decreasing values of x (say to the left), while $\cos (t - x)$ corresponds to a wave gliding towards increasing values of x (to the right). See for example the author's "Magnetic Circuit," p. 126. Thus we obtain the well-known result that a pulsating m. m. f. or flux of amplitude M may be resolved into two oppositely gliding m. m. fs. or fluxes, each of amplitude $\tfrac{1}{2} M$.

We now shall consider the real m. m. f. in each phase as being supplemented by a quadrature imaginary m. m. f. wave, and the resulting complex pulsating wave resolved into two oppositely gliding waves, as before. By analogy with equation (**18**), the expressions for these waves will be as follows:

$$\left.\begin{aligned} m_1 &= \tfrac{1}{2} M \exp. j\,(t + O + x + O) \\ &\qquad + \tfrac{1}{2} M \exp. j\,(t + O) - (t + O) \\ m_2 &= \tfrac{1}{2} M \exp. j(t + \delta + x + \delta) \\ &\qquad + \tfrac{1}{2} M \exp. j\,[(t + \delta) - (x + \delta)] \\ m_3 &= \tfrac{1}{2} M \exp. j\,(t + 2\delta + x + 2\delta) \\ &\qquad + \tfrac{1}{2} M \exp. j\,[(t + 2\delta) - (x + 2\delta)] \\ &\text{etc.} \qquad\qquad \text{etc.} \end{aligned}\right\} \qquad \textbf{(19)}$$

In these expressions the angle δ represents both the time and space displacement between two adjacent phases, that is,

$$\delta = 2\pi / n \qquad \textbf{(20)}$$

To find the resultant m. m. f. due to all the n phases, we have to form the sum of $m_1 + m_2 + m_3 +$ etc. It will be readily seen that δ disappears in all the second terms on the right-hand side of the equations (**19**). All these terms are equal to each other and their sum is equal to $\tfrac{1}{2} n M \exp. j\,(t - x)$. The sum of the first terms on the right hand side is equal to zero because

$$1 + \exp. j\, 2\delta + \exp. j\, 4\delta + \text{etc.} = 0 \qquad \textbf{(21)}$$

In order to see this, think of 1 in equation (**21**) as representing a unit vector. Then $\exp. j\, 2\delta = \cos 2\delta + j \sin 2\delta$ represents a unit vector turned with respect to the first one by the angle 2δ. See the author's "Electric Circuit," p. 94. Similarly the term $\exp. j\, 4\delta$ represents a unit vector at an angle 4δ with the first, or forming the angle 2δ with the second, etc. Thus, equation (**21**) represents a geometric addition of n unit vectors, each turned with respect to the preceding one by the same angle $2\delta = 4\pi / n$. Graphically such a sum corresponds to a regular closed polygon, that is, the sum of the vectors is equal to zero, whether n is an odd or even number.

Having proved equation (**21**) we apply it to the sum of the first terms on the right hand side of equations (**19**) by factoring out $\tfrac{1}{2} M \exp. (t + x)$, and thus show that the result is equal to zero. Consequently, the whole polyphase m. m. f. is due to the second terms and we may write:

$$\text{total complex m. m. f.} = \tfrac{1}{2} n M \exp. j\,(t - x) \qquad \textbf{(22)}$$

The imaginary part may now be dropped, and we obtain the following final result:

$$\text{total real m. m. f.} = \tfrac{1}{2} n M \cos (t - x) \qquad \textbf{(23)}$$

The resultant m. m. f. in this case is gliding to the right because the exciting currents have been assumed to lag in the consecutive phases from left to right. With an opposite assumption the resultant m. m. f. would glide to the left.

Discussion

R. E. Doherty: The scheme presented in this paper is highly useful, not only to electrical engineers, but also to mechanical engineers—indeed, useful in any problem which involves sine functions of time and in which the transient term is not of importance. And even if the transient is important, the particular solution of the permanent condition can be written down easily by this method. Making this possible, it certainly must be regarded, as the author says, a useful engineering "tool."

The paper does not emphasize sufficiently either the utility or the limitations of the scheme. For it is merely a scheme like other mathematical schemes, such as Heaviside's Operator, which works in some cases and not in others.

Of the three types of problems illustrated in the paper, the first is, I think, the most important in respect of the number of problems encountered in engineering, although of course its value in the rarer types 2 and 3, is also shown. And it is the former type to which the application of the method is the simplest. The author reviews how the addition of an imaginary term of equal magnitude to the real term, that is by the addition say of

$$j\,E \sin(\omega t + \gamma)$$

to

$$E \cos(\omega t + \gamma)$$

gives the vector identity,

$$E\,[\cos(\omega t + \gamma) + j \sin(\omega t + \gamma)] = E\ \epsilon^{j(\omega t + \gamma)}$$

that is, a vector of constant magnitude and rotating by the time angle ωt. Making a similar addition to each sinusoidal time variable in the problem, and substituting in the differential equation gives,[1] as each term, the product of a scalar quantity and a unit vector of the exponential form

$$\epsilon^{j(\omega t + \gamma)}$$

But $\epsilon^{j(\omega t + \gamma)} \equiv \epsilon^{j\gamma}\ \epsilon^{j\omega t}$

By thus separating out the time angle unit vector $\epsilon^{j\omega t}$ in each term, the vector may be canceled out of the equation, leaving only the product of a scalar, say E or I, and a stationary unit vector $\epsilon^{j\gamma}$ or $\epsilon^{j\alpha}$, where γ and α are phase angles of these vectors with respect to a common reference. The process therefore starts with the problem expressed as trigonometric functions of time, and ends with the problem represented as a system of staionary vectors.

Following out the process as applied to equation (**5**), gives

$$j^2\,\omega^2 L\,I\ \epsilon^{j\alpha} + j\,\omega\,r\,I\ \epsilon^{j\alpha} + I/C\ \epsilon^{j\alpha} = j\,\omega\,E\ \epsilon^{j\alpha}$$

Taking voltage as zero vector, and substituting $j^2 = -1$,

$$-\,\omega^2 L\,I\ \epsilon^{j\phi} + j\,\omega\,r\,I\ \epsilon^{j\phi} + I/C\ \epsilon^{j\phi} = j\,\omega\,E\ \epsilon^{j\phi}$$

where ϕ = phase angle between voltage and current.

Using vector notation,

$$\underset{\cdot}{E} = E\ \epsilon^{j\phi}$$
$$\underset{\cdot}{I} = I\ \epsilon^{j\phi}$$

and solving

$$\underset{\cdot}{I} = \frac{\underset{\cdot}{E}}{r + j\,(\omega L - I/\omega C)}$$

which is equation (**6**). But it should be remembered that E in (**6**), although the same notation as in (**1**), is nevertheless a vector in (**6**), but scalar in (**1**).

From the foregoing equations, it is obvious that *the process is equivalent to the substitution, directly in the differential equation, of*

$$\frac{d}{d\,t} = j\,\omega$$

and writing the variables as vectors.

That is, representing $\frac{d}{d\,t}$ by the usual notation p,

$$p = j\,\omega$$
$$p^2 = -\,\omega^2$$
$$p^3 = -\,j\,\omega^3 \quad \text{etc.}^2$$

In other words, the solution is immediately written down without, in each case, going through the process of substituting the imaginary term: which process, I fear, may appear to be necessary both from the text and the analogs given. The possibility of the above direct substitution would not, I think, be obvious from the paper to most engineers unfamiliar with these forms.

As to the limitations of the method: none is stated except that the variables against time shall be sinusoidal; but there are limitations which I believe are not obvious. A mathematical equation is applicable only under the assumptions it contains. In the present case, the fundamental assumption is that imaginary terms shall remain imaginary, and real terms, remain real. Thus no products must appear, since two imaginary terms multiplied together give a real product. I would therefore ask the Author: since in the method, each variable contains an imaginary component, does it not follow that, unless new definitions are added, the method is applicable only to *linear differential equations involving sinusoidal functions of time*; that is, it is *not* applicable, without new definitions, to equations involving products of variables, or products of a variable with the differential coefficient.

I mentioned at the outset thatthe method is useful in mechanical engineering problem. An illustration is the design of flywheels for reciprocating engines or compressors connected to synchronous machines. The equation[3] of the system of forces is

$$I\,\frac{d^2\,\theta}{d\,t^2} + T_d\,\frac{d\,\theta}{d\,t} + T_s\,\theta = f(t)$$

where

I = moment of inertia of rotating masses.

θ = mechanical angular displacement from a reference, rotating at the average, or synchronous, speed.

T_d = damping torque, corresponding to a phase shift at the rate of 1 mechanical radian per sec.

T_s = synchronizing torque, corresponding to one mechanical radian displacement.[4]

$f(t)$ = applied force as function of time. It is the fluctuating component of the crank effort; that is, the difference between the total impressed torque and that which is consumed as load and friction. Although of complicated form, it is resolved into a Fourier's Series, and each sinusoidal component considered separately.

Thus applying the method proposed in the paper,

$$-\,I\ \gamma_n^2\ \underset{\cdot}{\theta} + j\,\omega_n\,T_d\,\underset{\cdot}{\theta}_n + T_s\,\underset{\cdot}{\theta}_n = \underset{\cdot}{T}_n$$

where $\underset{\cdot}{T}_n$ and $\underset{\cdot}{\theta}_n$ are respectively the vector force, and vector displacement angle of the nth harmonic. Thus

$$\underset{\cdot}{\theta}_n = \frac{\underset{\cdot}{T}_n}{j\,\omega_n\,T_d + (T_s - I\ \omega_n^2)}$$

the phase angle between the force and displacement being

$$\phi = \tan\ \frac{\omega_n\,T_d}{T_s - I\ \omega_n^2}$$

Each component is thus computed, and plotted as waves to determine maximum.

I therefore consider the method proposed in the paper as a very important mathematical device, and have hoped by this discussion to encourage its greater use.

J. B. Whitehead: Methods of solution of differential equations are of especial interest in two connections, one when a new type of equation presents itself for solution, and the other when teaching the phenomena whose sequence is expressed by the form of the equation.

The complete solution of the simple a-c. circuit, the first example used by Professor Karapetoff in calling attention to the method of superposed imaginaries as an aid to solution, has been known for years. Consequently its chief value here must be only as an illustration of a mathematical method. However, there is an element of danger in the use of the method in this case, since it does not lead to the complete solution of the equation of the simple a-c. circuit. The transient term on closing the circuit does not appear and is neglected. As is well known, there are many instances in practise when this term is of great importance. Professor Karapetoff clearly recognizes this, and will doubtless reply that the exponential form may also be used for the complete solution, but in this case, as he well knows, all the simplicity of method to which he calls attention disappears. Therefore, for the purposes of teaching, in this case the method appears to me to have little value and, in fact, to be open to criticism. Its brevity and simplicity make a powerful appeal, but it does not completely cover the problem. While I have had the method in my notes for a number of years, as have many other teachers of this subject, I have avoided using it, feeling that in doing so I would shirk a measure of responsibility in not giving the complete solution.

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[1] Since either the differential or integral of an exponential is again the exponential.

[2] This was proposed in 1917 by Mr. A. Press in discussion of paper by V. Bush on "Oscillating Current Circuits," A. I. E. E., Vol. 36, p. 207.

[3] Equation (1) in paper on Flywheels, A. S. M. E. December 1920, by R. E. Doherty and R. F. Franklin.

[4] Obviously no such displacement could occur within operating limits. It is simply a proportionality factor which holds approximately in the limits considered.

In the second example the author is on very much surer ground. He presents an apparently new equation which demands solution. Here the simplicity of the method has apparently facilitated the solution, leading to conclusions which it was possible to check in practise. I have not read the original paper describing the experiments and I think it would be of interest if Professor Karapetoff would say a further word as to the agreement between the results to be expected by the solution of the equation and those noted in actual observation.

In the third case we have again a problem whose solution has been known for some time. The method therefore should be considered from the point of view of its usefulness in explaining the phenomenon involved. I confess that I do not see its value for obtaining the intensity of a gliding or rotating magnetic field due to a polyphase system of electromotive forces. The various transformations through which the author has to proceed in order to obtain the result, seem to me to confuse the comparative simplicity of the physical relations underlying the type of field in question as related to the circuits setting it up. By use of the ordinary complex expressions for the several electromotive forces, and their successive resolution into two directions in space, lead to simple series for the two sets of components which can be immediately evaluated in single terms. This method described by Steinmetz in one of his early works has the advantage of keeping clearly before us the simple elements of the exciting circuits and the resulting magnetic intensity.

Thus, while recognizing the simplicity and beauty of the method as applied to new unrecognized problems, I question its value for the purposes of explaining the phenomena represented by the equations.

P. Trombetta: The fundamental principle upon which all calculations of electric circuits are based, is that the constants of the circuit remain unchanged after an e. m. f. is applied to it. In Prof. Karapetoff's exposition it is tacitly assumed that the constants of the circuit remain also unchanged if we apply, instead of a real e. m. f., a complex one and since the application of a complex e. m. f. yields an easier solution, it is better to study the circuit by the application of a complex e. m. f. rather than a real e. m. f. If we replace the word e. m. f. by the word force, which may mean any kind of force whatsoever, and if we replace the word circuit by the word system, we have the generalized theorem that: the study of a system, which by the application of a force gives rise to oscillations and losses of energy, is always simpler when the force applied is sinusoidal and can be expressed as an exponential function of time.

W. V. Lyon: If I understand Prof. Karapetoff correctly he is, in effect, making a plea for the vector method of solving alternating-current problems rather than that method in which the instantaneous values of the quantities are represented by trigonometrical expressions. As a mechanism for solving problems in which the electromotive forces and currents vary sinusoidally a comparison of the methods soon convinces one of the superiority of the vector method. Unfortunately, as Prof. Karapetoff says, it is not widely appreciated to what extent the vector method may be used. We are all familiar with its application to the steady conditions in simple electric circuits and in a-c. machinery, and perhaps to a lesser degree, in long transmission lines. Moreover, it is exceedingly useful in the solution of the current distribution in round wires or in rectangular armature conductors, and of the flux distribution in transformer laminations. In these cases the angular velocity of the vectors is a real number. The letter "ω" is usually used. Rather recently it has been appreciated that the vector method can also be applied to the solution of the transient conditions that are obtained in transformers, synchronous and induction machines. This latest application gives an exceedingly powerful and simple method of attack. In the problem of the transient condition the angular velocities of the vectors are not real, but may be represented by complex numbers of the form $(-\alpha + j\,\omega)$. The ω gives the real angular velocity of the vector and the α determines the rate at which it shrinks exponentially.

While Prof. Karapetoff has made no direct plea for the vector method the writer has so chosen to interpret his argument. The symbolism $E\,\epsilon^{j\omega t}$ has been used to represent a rotating vector by mathematicians for many years, long before the notation was introduced into electrical engineering. There are, moreover, other simpler and just as powerful vector notations. The solution for the current density in rectangular armature conductors is very simply expressed in terms of hyperbolic functions, more simply the writer believes than in the manner Prof. Karapetoff suggests.

If we assume that the applied e. m. f's. vary sinusoidally, with either constant or damped amplitudes, and the circuit constants do not vary, all resulting currents will vary sinusoidally as do the applied pressures. In such a case we might well agree that it was superfluous to indicate this obvious variation. There can be no doubt but that this apparent lack of any convention to represent sinusoidally varying currents and pressures is extremely simple.

The writer looks upon it as fortunate that we have a variety of symbolisms that may be used in the solution of problems inasmuch as the student may choose for himself the method that best suits his understanding. Those who are not familiar with the notation that Prof. Karapetoff presents are thus indebted to him for bringing to their attention so powerful a method. After all, the best mechanism for the individual student to use in solving problems is that which is not only simple to manipulate but which keeps before him most clearly the physical reactions involved.

V. Karapetoff: Mr. Doherty is right in saying that in practical applications, in linear differential equations, is it perfectly safe to use $j\,\omega$ in place of $d/d\,t$ and $-\omega^2$ in place of $d^2/d\,t^2$.

This is, however, not a substitute method but a direct result of expressing the current as an exponential function. In equations involving products of complex quantities, if one of the quantities is simply an exponential impedance operator which does not contain time, the method is still applicable. But if an equation contains a product of an exponential current and an exponential voltage, the result is a double frequency power and a constant average power. A new convention is then necessary as to the interpretation of the results.

Dr. Whitehead doubts the advantage of the exponential notation when the transient term is not negligible. He will find Section IV of Dr. Steinmetz's book on "Transient Phenomena" treated in the exponential form to a good advantage. As to the third illustration in my paper, E. Arnold in his Wechselstromtechnik solves the same problem by means of sine and cosine functions, and I believe that a comparison will show a decided advantage in favor of the complete notation.

Questions on the Economic Value of the Overhead Grounded Wire

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Review of the Subject.—*Overhead grounded wires have been in extensive use since the construction of the earliest transmission circuits. The fundamental theory of their protective value is based on Faraday's ice-pail experiment. As the resulting law goes, there is no electrostatic field emanating from the inner surface of a charged hollow conductor. The parallel grounded wires do not surround the power wires. Consequently the protection of these grounded wires against induced electric charges by thunder-clouds, is only partial—usually of the order of 25 to 40 per cent.*

It might be erroneously inferred that several decades of use of the overhead grounded wire had established by practise its value. The several factors involved in its use do not lend themselves easily to experimental observations. For example, power lines extend over hundreds of miles, while any particular induced charge is localized at some point in these vast distances. Taking into account the brief period of a lightning stroke, the unwilling observer stands a small chance of being near the point of discharge. Furthermore, thunder-clouds differ from one another. Still further, at the instant the lightning bolt takes place the distance from the thunder-cloud to the power wires varies quite indefinitely. In fact, there is a long list of difficulties involved in experimental observation of the effect of cloud lightning on power wires. As a result, except for a few small-scale experiments performed in the laboratory, knowledge of the subject is confined almost entirely to theoretical analyses. This paper is an addition to the theory but it is not of a mathematical nature.

Conditions of protection have changed in recent times. Therefore, in this paper the definite conclusion is drawn that the expense of overhead grounded wires on wooden pole lines is, in general, an economic waste. In particular cases it may be justified. On metal tower construction the use of the overhead grounded wire is, in general, fully justifiable.

The analyses in this paper were made for presentation to a Public Service Commission. This Commission, on reconsideration, reversed its order that an overhead grounded wire should be installed on a 13-kv. transmission circuit supported on a wooden structure.

Review of New Material. — *References to the technical literature on the subject of overhead grounded wires are given in the bibliography which follows the paper. For those familiar with the subject there is given below a brief review of several parts of the paper which emphasize the recent additions to the knowledge of the subject.*

1. Analysis of the functions of the overhead grounded wire under nine distinct parts, where previously only three functions were classified.

2. Recognition that the requirements of the overhead grounded wire are less than formerly. In the early days the overhead grounded wire was needed to assist lightning arresters, but today the arresters have sufficient discharge rate not to require the assistance of the grounded wire.

3. Analysis which points out that the overhead grounded wire protects only for a specifically limited range of voltage. It is no protection for induced voltage below the normal arc-over value of the insulator, and no protection when the induced lightning voltage is sufficient to arc-over the insulator in spite of the presence of the grounded wire.

4. Appraisal of the weight to be given to each of the nine functions of the overhead grounded wire and considerations of its cost lead to the conclusion that, barring exceptional cases, it is an actual detriment when placed on semi-insulating structures, such as wooden pole lines. Used here the overhead grounded wire lowers the arc-over voltage of lightning.

5. The overhead grounded wire with considerable sag cannot be considered as a mechanical support to rigid tower structures.

6. Analysis is given to show that the overhead grounded wire on a metal tower line loses its function in protecting arc-over of insulators in proportion to the earth resistance at the legs of the tower. Experimental proof is not available at present. Also the values of ohmic resistance at tower legs which will destroy the protective value of the grounded wire to prevent arcing over insulators are not available. Metallic connections of a tower of high earth resistance to an adjacent tower of low earth resistance have little if any beneficial effect in protecting the insulator from lightning. The horizontal distance is too great.

7. On a grounded neutral system experimental tests of a short circuit of a single phase showed the necessity of connecting the overhead grounded wire to the station earth connection to reduce the earth resistance to a safe value. Otherwise the neutral rose so high in voltage during short circuit as to jump-spark into the low-voltage wiring of the station, blowing fuses and affecting the switch control.

8. Looking to the future, the overhead grounded wire, by lowering the general resistance to earth of all towers to the passage of accidental short-circuit current (of the generator, not lightning) will have a valuable function in connection with arc-suppressors. This function is really the one already recognized as an aid to proper operation of relays.

A General Conclusion.—*As applied to metal structures the analyses do not bring out any detrimental function of the overhead grounded wire. It is not condemned in this use but attention is directed to some of its limitations. Further study is desirable. The cost of the overhead grounded wire is a considerable factor. At maximum it now seems that for many or most cases one grounded wire only may be needed. Exceptional cases and conditions must be decided by detailed considerations.*

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DEFINITIONS

THE term "overhead grounded wire" is currently used to mean the extra wire, grounded at many or all of the supports, that is strung parallel to the power wires on an overhead transmission. The "aerial grounded wire" has also come into use to mean the same.

"Overhead" is a term more commonly used by electrical engineers of transmission lines than "aerial" as applied to grounded wires. Aerial, perhaps, is the more general term. "Overhead" usually carries the idea to most people as being above the power wires although it means literally above the head. Overhead may, therefore, mean literally underhung or overhung relative to the power wires.

The vertical grounded wire—the connection between the overhead wire and the earth contact—is used on wooden poles or other types of semi-insulators. As such it is sometimes referred to as the pole wire.

Earth connections are the metallic parts extending into the earth. The earth connection may be in the usual forms of tower legs, driven pipes, or coiled wire around the base of a wooden pole.

The lightning rod is any projection of conductor in the vertical plane above the horizontal grounded wire.

In review, the four parts are: 1, horizontal overhead grounded wire; 2, vertical grounded wire; 3, earth connections; and 4, lightning rod (seldom used).

HISTORICAL

It is not the object here to trace the growth of use of the overhead grounded wire but simply to bring out some salient points and to give a bibliography of the scientific discussions of this subject. The earliest overhead grounded wires were barbed wires, such as used by farmers. The Bessemer steel used in this wire (when used in the relatively long spans between poles) was so unreliable in mechanical strength that the wire gave much trouble from breaking and short-circuiting the power wires. It was early recognized that *the barbs on the wire had no practical value in giving protection against lightning strokes.* There was erroneous theory advanced by lightning rod experts that point discharge by corona materially lessened the danger of direct stroke. The theory seems unreasonable.

There have been few attempts to prove practically the value or uselessness of the overhead grounded wire but none of these has been convincing unless perhaps one instance given in a recent N. E. L. A. report, because of the variableness in the lightning storms and the impossibility of getting an exact comparison by any of the data collected. The reasonable basis of the good effects of the overhead grounded wire has resided mostly in the theoretical consideration. It is a comparatively simple matter, although laborious, to calculate the quantity of electricity induced on a transmission wire with and without a parallel grounded wire. These figures are quite definite. The theory has been substantiated by electrostatic measurement. While it was formerly the opinion of the majority of leading electrical engineers that the overhead grounded wire fully warranted its cost under certain conditions of installation and for a definite range of voltage, it is well, nevertheless, to make note of the fact that the practise is not founded on definite experimental knowledge of the actual installations. There are many doubters of its value nowadays.

INTRODUCTORY—MECHANICAL VS. ELECTRICAL FACTORS

The primary requisite of an aerial electrical line is to be ready to supply electrical power continuously. To do this two natural and fundamental conditions must exist, namely that the line must be suitably insulated to withstand all impressed voltages and, second, that it must be mechanically durable. The mechanical durability involves the mechanics of material, their strength, characteristics, etc. While the factors involved in the mechanical side of the line construction are of prime importance, it is not the object in the present discussion to treat of them except as the type of mechanical construction influences directly the dielectric strength of the insulation. To confine the discussion as much as possible to the electrical side, it is assumed initially that due weight has been given to all the engineering factors and the choice has been made of construction with porcelain, glass, wood, cement, concrete (with or without reenforcing), or steel, together with such impregnating or painting treatment as the conditions demand. The mechanical structure may then be analyzed into types according to the insulation it affords against electrical failure. Steel structures represent one type, wooden poles represent the other.

The prime object of the present discussion is to treat the electrical side, especially in the matter of insulating against lightning and the line potentials. The specific subject to be treated is indicated by the title, "Overhead Grounded Wires." It is of course, impossible to treat of the aerial wire by itself, as the whole aerial system of electric wires and supports must be taken into account as in any engineering structure. The first question we must ask ourselves, then, is: What is the object in using an overhead grounded wire?

The answer to this question differs now from what it was in earlier days of transmission. This fact is one of the excuses for this paper. In early days lightning arresters were uncertain and of low discharge rate. Insulation was weak and not wisely distributed. As a result, the overhead grounded wire was desirable to lessen the duty on lightning arresters. This necessity has disappeared. While it is not claimed that the proper value of discharge rate for an arrester is exactly known for every application, each arrester of the valve type is capable of adjustment to a much higher value than used at present which, in the limitations of present knowledge, seems to be sufficient.

Speaking from the electrical standpoint solely, a partial answer sometimes made is: To lessen the electrostatic induction on the power wires caused by thunder-clouds. Faraday in his "ice pail" experiment showed that no electrostatic lines of force extend into a closed conductor. The earliest writers on protection of lines state that if an aerial transmission line could be entirely surrounded by a metallic sheath, such as is done with the lead encasing sheath of an electric cable, no electrostatic induction from the clouds on the power wires could take place. Such a construction has not been found economically feasible. An amelioration only of the induced voltage has been gained by the use of one to three aerial grounded wires. Lead-encased aerial cables are common practise in telephone construction. In power transmission such practise is limited by the cost of electric cables and the difficulties of obtaining suitable insulation material for very high voltages.

A more complete analysis than has previously been given of what can be expected of overhead grounded wires follows. It is not the ultimate of the possible detail analysis but is made from the viewpoint of the engineer in the process of determining the need, the value, and the desirability of this protective device.

FUNCTIONS OF THE OVERHEAD GROUNDED WIRE

The functions of the overhead grounded wire may be put into nine main divisions, as follows:

1. *To reduce the quantity of electricity and the energy induced on the power wires by a lightning cloud and to reduce the voltage of a traveling wave* (with its energy located between lines and ground) which was previously the "bound" charge held by the electric induction from the overhanging thunder-cloud. This function reduces the charge and energy that reach the apparatus and arresters. In the usual location of the overhead grounded wire it gives no appreciable protection against those internal surges which have their energy located between power wires.

2. *As a protection of insulators against flash-over.* This second category is to be distinguished from the first, especially in such a respect as involves the time. If flash-over takes place it should happen while the surge energy is crowded toward a point on the line, a time presumably coincident with the movement of charges in the cloud, and not after the charge splits into two parts and travels away from this point. This theoretical matter will be taken up again under the heading "Steel Structure."

3. In some cases the use of the *overhead grounded wire as a mechanical support between towers* is of greater value than its electrical protective functions. Occasionally, however, during sleet storms accompanied by transverse winds it is a disadvantage in throwing an extra side pressure onto the towers. Even its value as a longitudinal mechanical support for rigid towers is questioned later.

4. The overhead grounded wire has in some cases a very useful function in *forming a low-resistance earth connection.* There are four aspects to this factor: (a) As a uniform earth connection the parallel grounded wire may be used in *localizing faulty insulators.* (b) Where the neutrals of the power circuits are grounded the lesser resistance of earth connection is an aid *during accidental single-phase short circuits in preventing a rise in voltage of the station ground* and consequent damage to the low-voltage wiring of the stations, including circuit-breaker control, lights, excitation, etc. This is an important function only recently recognized. Some experimental experiences will be described at some future time. (c) Where towers are set in dry earth or rock and thereby partially insulated, the overhead grounded wire may become valuable in *connection with the arc suppressor.* The multiple earth connections supply good conduction to earth in spite of those towers that are practically too insulated to give proper operation of selective relays used in conjunction with the suppressor. (d) There is also a probable, remote value, in cases of dry or rocky foundation at towers, relating to the question of *danger to human life* for anyone standing on the ground and in contact with the tower when an insulator on the same tower is accidentally short-circuited.

5. *The overhead grounded wire absorbs a part of the energy of a traveling wave on the power wires.* It thus lessens the discharge current through lightning arresters when the lightning cloud is at a distance from the station.

6. When used *near a station* and when a *direct stroke* occurs near the station, it is possible that the overhead grounded wire lessens the chance of high voltage entering the station.

7. In the type of distribution circuit known as the *three-phase, four-wire* system the fourth wire is usually grounded at one or more places. The primary object in the use of this parallel grounded wire is not for protection against lightning. The use is economic in origin. Standard 2300-volt transformers Y-connected give a line voltage of 4000 volts. The higher voltage of transmission permits a saving in copper of the wires, if the power delivered is greater than can be carried on the minimum size of wire chosen by reason of mechanical strength. There is also a saving in lightning arresters at single-phase installations. Only one main arrester is used at the transformer of a four-wire system where two main arresters are needed for a single transformer on the three-wire system.

Incidentally the presence of the fourth wire decreases the lightning voltage induced on the remaining power wires.

8. *On single-phase short circuits,* with neutral grounded, the overhead wire acting as a partial return wire *reduces somewhat the inductance.* This reduction may be somewhat beneficial or detrimental, according to conditions and requirements of circuit breakers and relays.

The overhead grounded wire lessens the stray electric field which would extend to a parallel telephone or other low-voltage line and thereby lessens somewhat the inductive interference which must be neutralized by transpositions in both circuits.

Comments Before Noting the Ninth Factor. The eight foregoing functions of the overhead grounded conductor, in so far as they are performed, are preponderatingly beneficial in their general effect on an electrical transmission (not to say economically desirable). The ninth and last tabulated function may, in some types of construction, become very detrimental.

9. *The overhead grounded wire brings the zero potential of the earth from its surface to the height of the overhead grounded conductor in the near meighborhood of the power wires.* This lowering of the potential of lightning induction in the neighborhood of the power wires is the fundamental reason for the decrease in the quantity of induced charge as described in the first enumeration.

The nearer the grounded wire to the power wire, the less the induced static charge and voltage by thunder-clouds on the power wires. *But the reduction of this lightning potential is not the ultimate desideratum in using the aerial grounded wire. The real aim is to lessen the number of flash-overs at the insulators.* For purposes of illustration the effect of different distances between power wires and conductors at zero potential will be discussed. In the extreme minimum, if the grounded wire is placed too close to the power wire its presence increases the number of flash-overs, due, not to lightning, but to the power potential itself. From this consideration alone then a mechanical clearance throughout the spans between supports must be maintained sufficient to give a suitable spark voltage to the power wires. The spark potential between the power wire and the parallel grounded wire should, in general, be greater than between the power wires and their conducting support at the insulator. The object of this ruling is to avoid damage to the grounded wire by the tendency of the craters of accidental arcs to melt the wires in two. Such safe spacing is easily obtained for grounded wires used on metal towers. It is seldom attained on wooden-pole construction and other means are necessary to avoid damage by craters. A discussion of these means will be deferred.

RELATION OF OVERHEAD GROUNDED WIRES TO CLOUD LIGHTNING

Erroneous functions have sometimes been attributed to the overhead grounded wire. To counteract these speculations, occasionally heard, some statements will follow of what the overhead grounded wire does not do.

It has no effect in lessening the formation of electric charges in the clouds.

It does not increase or decrease the number of lightning flashes from the clouds.

It is not known to have any effect in either dissipating or producing appreciable charges in its neighborhood. Even the ionization produced by corona at the surface of a wire must be rapidly lost at a small distance from the wire. Otherwise, the power potentials would spark from wire to wire. If very high potentials in the future, by some unknown, incipient effect, are going to ionize or deionize the atmosphere to a radial distance sufficient to have an effect on a lightning stroke, it is a matter to be determined by future research. Even if some new very high potential power circuit gave evidence of gradually discharging atmospheric charges in its neighborhood, rapidly traveling thunder-storms (the most common form) would still be blown over the power lines.

The electrostatic potential rise in a thunder-cloud usually precedes a discharge by only about one minute. This is a short period in which to expect any relief of strain in the atmosphere around a transmission line by any known corona effect produced by the thunder-cloud.

So far as known at the present time, the value of the overhead grounded wire is entirely in relation to the power wires which it parallels.

It is presumed that the overhead grounded wire parallel to the power wires probably exerts slight effect in reducing the voltage induced electromagnetically by those little-known rare discharges which parallel the transmission line but take place from cloud to cloud.

Pertinent to what the overhead ground wire cannot do is an effect sometimes attributed to iron deposits in the neighborhood of storms. In a court-room the statement was made that iron deposits increased the frequency and severity of electrical storms. This statement is erroneous although it has enough element of fact in it to resemble the truth. The electrical charges gather in the atmosphere independently of any formation under the surface of the earth. However, any condition of electrical conduction which lowers the resistance in the path of the lightning bolt increases its current and prolongs the duration of the discharge. The conduction of bonded rails of railways produces burning effect in lightning arresters, having spark gaps, notably more severe than when there are no rails to gather in the radially traveling charge on the earth's surface. Salt swamps it might be argued would have the same effect. The writer has no data on the path the lightning might take either along the surface or (by leaving the static pull) spreading to better conducting layers at more or less depth beneath the surface. Incidental to this subject, a study of earth pipes showed that the whole earth became a good conductor at short distances from the contact with the pipe, due not to high conductivity, but to vast cross-sections. There are, in fact, several unknown relations in the discharge path of lightning that form a field for speculation, such for example as the ohmic resistance of the feeding arteries in the cloud, the main artery, the earth contact, and the unknown path of the gathering currents on and in the earth under the discharging cloud.

DETRIMENTAL EFFECT OF GROUNDED WIRES ON A SEMI-INSULATED STRUCTURE

The very presence of an overhead grounded wire anywhere on a well-designed wooden-pole structure reduces the spark potential to lightning stroke. Its presence must therefore, in this particular respect, be considered detrimental. It is detrimental somewhat in proportion to the decrease it causes in the spark voltage between the power wires and ground. For example, a normally insulated wooden-pole line, without overhead grounded wires, has a spark voltage to lightning proportional to its height above the surface of the earth. It is of the order of magnitude of 10 to 20 meters (33 to 66 feet). The distance from the power wire to the grounded wire is usually of the order of magnitude of 1 to 2 meters (3 to 6 feet). Thus the presence of the grounded wire on a wooden-pole line reduces the spark potential of induced lightning stroke to one-fifth or one-tenth. The result of this decrease is shown in a greater number of insulator flash-overs due to lightning.

To summarize this discussion crudely in a single sentence: Placing an overhead grounded wire on a well-designed wooden-pole line lowers its spark potential 80 to 90 per cent in order to lower the induced potential of lightning by a value of the order of 25 per cent.

RELATION OF GROUNDED WIRE TO DIRECT STROKE

So far as the aerial grounded wire carries zero potential above the surface of the earth it increases the possibility of direct strokes on the line. As a matter of judgment this increased probability of direct stroke is entirely negligible if not absent where metal towers are used as a support. The tower will naturally take the discharge of the direct stroke, other things being equal. The presence of the grounded wire between towers slightly increases the possibility of a stroke finding a path to the circuit.

In the case of wooden or other insulated supports the presence of the vertical wire actually decreases the distance from the earth to the lightning stroke by 10 to 20 meters in a vertical direction. If the direct stroke comes so near the line that this decrease in distance shortens down appreciably the path of lightning stroke to earth it will, in proportion, invite the discharge to strike the grounded pole rather than some other object in the neighborhood. For example, a metal mast of a ship at sea in a thunder-storm will "draw" a lightning stroke to it from a considerable radius because it is the only high point on a smooth surface. Analogously a wooden pole having a vertical grounded wire and located in a flat country should slightly "draw" a lightning stroke that happens to come in the near neighborhood. Direct strokes on transmission lines are relatively rare. This being so how are we to give weight to the factor which has a possible slight effect on increasing the rare event?

In cases of direct stroke on a wooden pole the vertical wire on the pole prevents splitting of the pole by the explosion coming from the sudden vaporization of the moisture in the wood by I^2R of the lightning current and ohmic resistance of the wood. The writer has never heard of but one case where the pole was destroyed as a support. Many cases of slight and serious damage to a pole are known. Fig. 1 shows severe damage to a pole by lightning. This experience brings up the question, important to the best type of construction, for power lines, is it worth while to invest in vertical grounded wires on poles, and thereby decrease the insulation of the line against lightning, to save that apparently rare case of complete destruction of a pole? Those who may add information, either in discussion to the present paper or in those valuable reports of committees such as in the N. E. L. A. now gathering information, should make a distinction between poles burned by dynamic current and poles destroyed by lightning. Lightning does not carbonize the wood—it explodes the moisture. The distinction is desirable because the cure is different. The vertical grounded wire, while preventing the damage by a direct stroke of lightning, increases the accidental burning effect on crossarms by the power voltage by increasing the potential gradient along the crossarms. When the vertical grounded wire short-circuits the high resistance of the wooden pole it throws the line-

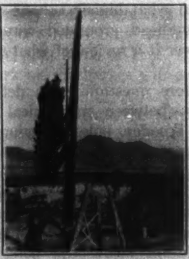

FIG. 1—NEWLY ERECTED POLE STRUCK BY LIGHTNING, AUGUST 7, 1916, NEWTON, UTAH.
By courtesy of the Power Company.

to-ground potential on the part of the crossarm which is situated between the wire in accidental connection with the crossarm, and the bolt at the junction of pole and crossarm. This distance is of the order of one meter. On the other hand, if no vertical grounded wire is used the same potential is distributed over the sum of the distance along the pole and crossarm. The greater resistance to earth decreases the leakage current and lessens the risk. This distance is of the order of 4 to 7 meters.

OVERHEAD GROUNDED WIRES ON WOODEN-POLE STRUCTURES

Attempts to induce public service commission to specify the use of overhead grounded wires on wooden structures has raised the serious question whether the overhead grounded wire so used is not an economic waste. On comparatively low voltages on wooden poles it surely is a loss unless it is installed for a purpose other than lightning protection. When the question is raised, at what higher voltage on wooden-pole lines should overhead grounded wires be used?—it requires to answer it a review of what useful functions it may perform.

However, before questioning in detail, distinction must be drawn between mechanical and electrical consideration. Wooden poles carrying grounded insulator-pins constitute admittedly a wooden structure from a mechanical standpoint, but it is a metallic structure from an electrical standpoint. Electrical protection of overhead grounded wires is under discussion. To discuss these questions logically the four grades of insulation below the porcelain insulators must be included as factors and each given its proper weight in the appraisal. These grades are:

(a) Nonmetallic pins, crossarms, and poles.
(b) Metal pins, nonmetallic crossarms, and poles.
(c) Metal pins, metal crossarms, nonmetallic poles.
(d) Grounded metal pins

Even the foregoing analysis is not definite enough unless by the two mechanical designations, metallic and nonmetallic, the idea of conduction and a degree of high resistance respectively are understood. For conditions attending the use of suspension insulators the distinction should likewise be made, but with different words because it is the cap and not the pin of the suspension insulator that is mechanically connected to the crossarm.

Grounded metal pins fall in a class with the metal towers and are not under analysis at present. The first three classifications, viz., (a), (b), and (c), are near enough alike to be treated with approximation in one class for the following analysis.

An attempt will now be made to apply in detail the general analysis, already given in nine functions, to the particular use of an overhead grounded wire on a wooden-pole structure.

First Function. On nonmetallic structures the overhead grounded wire is not needed as an aid to lightning arrester.

Second Function. Instead of protecting, it actually lowers the arc-over of insulators subjected to a lightning voltage.

Third Function. The overhead grounded wire is not needed for mechanical strength where pin-type insulators are used. It is detrimental in increasing the wind and sleet load.

Fourth Function. It may find some use as a low-resistance earth connection. Is it needed to localize faulty insulators? Not where wooden pins are used; and is of possible but doubtful economic use where metal pins are used. The vertical grounded wire makes a grounded pin where metal crossarms are used and therefore falls in the other classification. As making a better ground connection for a system using the grounded neutral the overhead grounded wire may be valuable, but for it to act in this capacity it is not necessary to install it for the full length of the power line but only near stations. Furthermore, as such, it is better to hang it under, rather than over the power wires. So located it cannot, after corroding with age, fall on the power wires. As an auxiliary to the arc suppressor (now under development) it seems of no particular use. It does not safeguard human life—the wooden pole is safer.

Fifth Function. In the fifth function as an absorber of traveling waves the overhead grounded wire is useful but not necessary. It is not needed to aid distant arresters. It is not necessary for isolated installations of transformers along the line which has no arresters. There are other and cheaper ways of getting protection.

Sixth Function. The overhead grounded wire may be used if desired near a station, with special precautions in construction, for use against direct stroke and yet save the expense for the rest of the lines.

Seventh Function. At present the three-phase, four-wire economics are not under discussion.

Eighth Function. As a return wire and a parallel conductor to lessen the scattered electrostatic field, the overhead grounded wire has its normal useful function. Except for very high voltage, prominent harmonics, and near parallel telephone lines this factor will seldom justify the expense.

During accidental grounds the value of the overhead grounded wire in decreasing interference with parallel telephone systems is reduced to a small, but unknown value by the predominant electromagnetic induction of the return currents in the earth.

Ninth Function. In bringing the zero potential of the earth from its surface to the height of the power lines the installation of an overhead grounded wire on an insulated structure is very detrimental. It reduces the arc-over voltage from the power wire to ground. This is the factor which seems sufficiently prominent to condemn the use of the overhead grounded wire on wooden structures.

Conclusion. Having considered briefly each of the separate items, the conclusion is reached that the overhead grounded wire is, in general, a detriment rather than an asset to a semi-insulated or high-resistance pole-line structure. It is impractical to consider here every possible detail but the endeavor has been made to mention or indicate all the factors, so that for any particular installation, engineering basis for the installation or taking down of an overhead grounded wire may be determined.

STEEL STRUCTURES AND THE OVERHEAD GROUNDED WIRE

The ninth function enumerated for the overhead grounded wire which is so objectionable to wooden pole construction is not so for steel structures. The metal tower or pole brings the zero of earth potential to the height of the line in the neighborhood of the insulators. The overhead grounded wire adds nothing more to this detrimental condition. All of the first eight functions enumerated for the overhead grounded wire are more or less beneficial and none is detrimental. Specifying the use for metal structures will depend on figuring enough intrinsic value to pay for its cost. A review of some of the crucial factors follows:

Such effective protective apparatus can be installed at the stations as to make the use of the overhead grounded wire all along the line of no particular need to help the arresters.

Suppose the overhead grounded wire is considered as a mechanical support in the accidental emergency of a broken power wire. How much good can it do? Can the overhead grounded wire prevent mechanical damage to the tower sufficient to maintain service on other parallel circuits? Considerations of the flexible structure support are set aside. The overhead grounded wire is an intrinsic part of it. The usual four-legged tower is a relatively rigid support. The overhead grounded wire itself is a flexible horizontal support. It sags loosely between towers. Can a tower top move, without damage to itself, far enough in the longitudinal direction to utilize the increase in tension of the overhead grounded wire? If not, the overhead grounded wire loses its value in this function. Will enough mechanical damage be saved to the local structure and other parallel circuit or circuits on the towers to warrant the cost and depreciation of the overhead grounded wire in its entire length along the tower line?

Will the overhead grounded wire decrease the number of flash-overs of the insulators? According to the theory given by the writer in 1916 (TRANSACTIONS A. I. E. E., p. 945) it may not have much value. This theory has not been refuted, nor even questioned. It states that the voltage of the induced charge on each power wire by thunder-clouds is decreased by the presence of a parallel grounded wire only by the passage to earth of the initial charge on the grounded wire and its replacement by an induced charge of the opposite sign by the lightning charge on the power wire. Under some conditions it is questionable whether this "increased capacitance" by the grounded wire becomes active in reducing the induced potential in time to save the over-stressed insulator from arc-over. This matter will be discussed further.

Among the factors which determine the efficiency of the grounded wire in preventing arc-over of insulators are some which are obscure, due to lack of both theoretical and experimental data. The time involved in the movement of the charges in the clouds is unknown. De Blois in 1914 gave some oscillograms which showed that some of the effects of potential changes in the cloud were very slow as compared to spark lag of insulators and gaps. So far as this slow movement obtains it is favorable to effective action of the overhead grounded wire. It is understood, however, that the final stroke to earth takes place with great rapidity but no one knows that this velocity in any way approaches the velocity of light which is the approximate velocity of travel of a free charge along a transmission line. It is hoped that some of Prof. Harris J. Ryan's unpublished work on discharges will add useful information to this subject.

At any rate, we know that the circuit of the cloud lightning is long as compared to the circuit of the grounded wire. This much information would lead us to infer that, in so much as affected by distance of travel, the charge on the grounded wire would have plenty of time to pass to the earth while the main bolt is taking place from cloud to earth.

There is a factor, however, in the grounded wire circuit which has not been given practical attention, namely the resistance of each tower to earth. There are many dry localities and even rocky localities in wet countries where the ohmic resistance of the earth connections of particular tower legs is extremely high. This resistance limits the rate of discharge of the freed charge on the grounded wire. In so doing it decreases the effect of the grounded wire in preventing arc-overs of insulators. While a calculation of the theoretical value of the overhead grounded wire with well grounded legs gives a potential ratio with and without this protection of about 70 per cent (a protection of 30 per cent) for a circuit of approximately the same dimensions as the Mississippi River Power Company's 110-volt line, a high resistance of earth connections would reduce this protection from 30 per cent to an unknown smaller value.

A proof of the small value of the overhead grounded wire to prevent arc-overs of insulators can be given by a simple arithmetical example.

Suppose the insulators in use on a line can be arced over by a lightning potential of 200 kilovolts. Suppose furthermore, that the tower legs have a high earth resistance and therefore the presence of a grounded wire would reduce the induced potential on insulators by only 12 per cent. It would then require an induction equivalent to 227 kilovolts to arc-over an insulator where the grounded wire is in use (200 ÷ 88 per cent = 227). If the induced voltage is less than equivalent to 200 kilovolts the presence of the overhead grounded wire has no value in preventing an arc-over. In fact, there would not be an arc-over if the protective wire were absent because the induced voltage is below the arc-over voltage of the insulator.

On the other hand, if the induced voltage is equivalent to 227 kilovolts the presence of the overhead grounded wire gives no useful results, because an insulator will arc-over in spite of the presence of the overhead grounded wire.

For all induced voltages below 200 kv. and above 227 kv. the parallel grounded wire, with a 12 per cent protection, has no value in preventing arc-overs. It is only over the small range between 200 kv. and 227 kv. that it would be effective. The chosen percentage of protection may actually be higher or lower according to the earth resistance of the particular tower where the maximum lightning voltage concentrates. A distinction is made in passing—while the overhead grounded wire decreases the general resistance to earth for power currents, it does not do so for lightning. Theoretically there is not sufficient time for the charge to flow to adjacent towers before the strain on the insulators produces its effect.

If this proof is sound it shows why observations made on transmission lines with and without overhead grounded wires have given so few useful data.

There is another useful viewpoint. If, instead of assuming the pessimistic conditions of protection, it is assumed that the tower legs are connected to earth with high conductance and other attendant conditions are such as to give the overhead grounded wire its maximum calculated value of 30 per cent protection, it may be considered as a very economical equivalent of an increase in dielectric strength of the insulators by somewhat less than 30 per cent; in other words, that the grounded wire is equivalent to putting extra disks on every line on the tower. The use is limited to lightning voltages. Protection is not given by the grounded wire against internal surges or, obviously, against failure of individual disks in a string.

On some general measurements made between two tower lines, the writer was led to believe that the usual resistance of earth connections of towers was high rather than low. Estimates made from related data and laboratory experiences indicate a restricted if not doubtful protection of insulators from arc-over by the overhead grounded wire when the insulators are on towers of high earth resistance. There are not enough data at the present time to give definite solutions to this problem. It would seem, however, that the problem is solvable.

To summarize the points gained so far in the analysis of metal support structures, the overhead grounded wire is not detrimental but is unnecessary as an aid to lightning arresters and it may have a small average useful range of protection for flash-overs of insulators.

On the other hand, for one purpose it seems there is going to be an incontestable use for the overhead wire on metal structures. This use is in connection with the arc suppressor which seems destined to become a standard device where aerial wires are used. As matters of development stand today the conditions needed are either very high resistance to earth, such as found on wooden-pole lines, or very low resistance to neutral such as can be obtained on metal tower lines linked in metallic contact by the overhead wire.

If the conditions are such as to make its use solely to lower the earth resistance in general, why not use it near the telephone line and even as a messenger wire? Induction on the telephone can be modified thereby. It will surely lower the voltage to earth induced on the telephone lines and make them safer to handle.

The work of this paper represents several days of concentrated effort. This is not enough for the complexity of the problem. The analysis is incomplete. More and specific experimental data are needed—data both from the laboratory and from the field.

The reasoning should be carefully scrutinized, and criticised especially in regard to its applicability to special cases.

SIGNIFICANCE OF THE ANALYSIS

The course of reasoning brings the conclusion that overhead grounded wires and vertical grounded wires on semi-insulating structures, such as wooden poles, are in general detrimental. On metal structures no technical function is found detrimental. If protection against arc-over of insulators is, as it appears, affected by the ohmic resistance between tower legs and earth either the effectiveness of the overhead grounded wire may be increased by attention to earth connections or this function of the grounded wire is sufficiently decreased to allow the grounded wire to be used lower down on the tower in another function. The relation between the earth resistance and the decrease in protection to insulators is yet to be determined.

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Note. The principal papers in the following list involving the theory of the overhead grounded wire are: 1 *by R. D. Mershon* (1903) *with its discussions;* 3 *and* 4, *discussion by Dr. Steinmetz* (1905) *and* (1906); 5, *by R. P. Jackson* (1907); *and* 12, *by E. E. F. Creighton* (1916).

1. Mershon, R. D. The Grounded Wire as a Protection against Lightning. Vol. 22, 1903, p. 331, 2000 words.

Discussion (5800 words) by Messrs. Scott, Perrine, Mailloux, Wurts, Thomas, Kennelly, Lincoln, Woodward, Rushmore, Kelsch, Kelly, Hayward, Waters, Curtis, Jackson, D. C., Hammer, Blanck, and Mershon.

2. Report of Committee on High-Tension Transmission. Questionnaire on Lightning Protection. Vol. 23, p. 592. (500 words on overhead grounded wire, practise but no theory).

Discussion largely overhead grounded wire (1400 words) by

Messrs. Finney, Mershon, Junkersfeld, Arnold, Schuler, Storer, Perrine, Clark, E., Jackson, W. B., Neall, and Lyman.

3. Discussion by Dr. Steinmetz, Vol. 24, 1905, p. 995. (400 words).

4. Discussion by Dr. Steinmetz, Vol. 25, 1906, p. 428. (600 words.)

5. Jackson, R. P. Potential Stresses as Affected by Overhead Grounded Conductors. 1907, Vol. 26, p. 873. (2800 words, 7 diagrams of equipotential curves).

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11. Short discussion of overhead grounded wires in five distinct papers beginning with a questionnaire of the High-Tension Committee, June 1911, Vol. 30 (12,000 words), by Messrs. P. H. Thomas, J. P. Jollyman, W. S. Lee, M. Hegben, and P. T. Hauscom, respectively.

12. Creighton, E. E. F. Theory of Parallel Grounded Wires and Production of High Frequencies in Transmission Lines (1916), Vol. 35, Part 2, p. 845 (17,400 words) 33 illustrations, 1 table, 41 mathematical equations.)

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OTHER SOURCES

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Discussion

W. W. Lewis: In this paper Mr. Creighton draws the conclusion that the overhead grounded wire is in general a detriment to a semi-insulated or high resistance pole line structure. By this I understand that he means not only the horizontal continuous grounded wire but also the vertical grounded wire that is applied to individual poles.

I believe that the experience of operating companies in general will not bear out this conclusion. While it is true that there has been considerable trouble on some systems due to the overhead grounded wire, this has been mainly on account of the fact that the ground wire was not put up with the same care and idea of permanency as the power conductors, with the result of breakage, and interference with the conductors. Also in some cases the insulators were small for the voltage and the presence of the ground wire further reduced the factor of safety. Where the ground wire is adequately installed and the insulators have a reasonable factor of safety, I believe that the ground wire is of great benefit in protecting the insulators and poles. The testimony of a few power companies in this respect will be interesting.

The Southern Power Company has overhead ground wires on practically all of its 2200 miles of 100,-44-and 13-kv. lines. It is its belief, based on experience, that ground wires afford considerable protection from lightning disturbances. The ground wires increase the mechanical stability of both pole and tower circuits and in case of pole lines prevents splitting of the poles by lightning.

The Idaho Power Company has had considerable trouble with overhead ground wires due to mechanical difficulties and is not putting them up on new circuits, in fact has removed them in some cases. However, it has had considerable pole shattering where lines were not protected by ground wire and has cured this by grounded bayonets at the individual poles. Its experience has led it to favor this class of construction.

The Utah Power and Light Company makes a practise of placing a metal band around the tops of its wooden poles and grounding this band. The conductors are in general arranged in a triangle with the top wire supported by a pin carried at the top of the pole. Wooden pins are used. Its experience with this construction has led it to believe that it has averted numerous cases of shattered poles and broken insulators. Operation without the metal band grounded, led to many cases of shattered poles. This construction cannot be used if the insulators are inadequate, as it will lead to shattering of insulators. Practically all of its 475 miles of 44-kv. line is equipped with the grounded metal bands, which its experience has led the company to favor.

Other companies have reported similar experiences which is contrary to that predicted by Mr. Creighton. A questionnaire directed to these operating companies would no doubt elicit a great deal of valuable information along this line.

C. L. Fortescue: On my trip last year to the Pacific Coast, I had some questions asked me about the grounded wire for protection, and I also elicited a good deal of information about it. A questionnaire was sent out recently by the N. E. L. A. in which experience with the grounded wire was asked. A number of people told me that the questionnaire was not always treated seriously, that the replies could not be depended upon, and that a lot of the companies that were questioned about the use of grounded wires had never installed grounded wires properly.

This seems to agree with the statements of Mr. Lewis. Where grounded wires have been properly installed, they have given a good deal of protection, I believe.

Mr. Creighton's theoretical explanation of the grounded wire, I think is not quite adequate. The grounded wire is used to increase the capacity of the transmission system as a whole to ground, so that if there is a charge induced on the system, when the charge is released as for instance by the discharge of a thunder cloud, the potential of the surge will be limited in value in inverse proportion to the capacity. Any means which increases the capacity of the system as a whole to ground, will give correspondingly lower potentials, due to lightning effects. I was talking to the engineer of the Byllesby Company some time ago about the use of grounded wires, and he told me that his company was going to continue their use, and he thought they did good. He said that according to the general method of putting up a grounded wire it was considered as something that could be stuck up in any way at all. According to his ideas the same class of construction should be used for installing a grounded wire as in the case of the transmission lines themselves, and that if this practise were carried through, with proper maintenance, the protection obtained was good.

E. P. Peck: Mr. Creighton referred to a case which came up recently regarding the use of an overhead ground wire in a small system in New York State. The president of the Company operating that system had been ordered to install an overhead ground wire in connection with a 13,200-volt circuit which had been reported as giving adequate service without the overhead ground wire. The president objected to installing the overhead ground wire, and he wrote a large number of letters to most of the representative companies in New York State, and also to a number of large transmission companies and management corporations throughout the country. The gentleman was kind enough to send me a copy of all of the letters, which I very carefully reviewed. Of the 78 replies to his questionnaire, 72 were against the use of overhead ground wires, 2 were non-commital, and 4 were in favor of overhead ground wires on transmission lines. I was very much pleased to find that the consensus of opinion as shown in these letters were so overwhelmingly against the overhead ground wire, because they confirmed my operating experience. Had the questionnaire been sent out ten years ago, I dare say the majority of the opinions would have been favorable to the overhead ground wire, as a good many theoretical considerations would indicate that the overhead ground wire is of considerable value. My operating experience, however, has caused me to very definitely decide that the overhead ground wire is a source of trouble.

On one line in the South, which was equipped with an overhead ground wire, we had a large amount of trouble. The line was re-insulated and at the same time the ground wire was removed. After the re-insulation the line gave practically no trouble, and we concluded that the ground wire had not done any good, in fact indications showed that the presence of the ground wire caused considerable additional burning to the cross-arms and pins. Since that time, and in connection with a number of different lines, the same experience has been repeated to a greater or less extent. We do not now put an overhead ground wire on wood pole lines under any conditions, and probably never will unless some new evidence comes up.

Our results indicate that the overhead ground wire does more harm than good, not due to its falling or breaking, but due to the fact that it puts ground potential close to the conductors and reduces the insulating value of the wood pins, cross-arms and poles.

In Utica we put up several transmission lines of intermediate voltages without overhead ground wires. On these lines we have had only one pole shattered, that I recall, in two years. The insulators were not damaged and the pins and cross-arms were not burned. We have not lost a single insulator on these lines. On the other hand we have lost something like 15 insulators, due to flash-over, on our steel tower lines equipped with overhead ground wire, in about the same period, though the steel tower line is insulated with excessively large insulators which had not been in service as long as a year at the time of the failure.

It is my definite opinion that the overhead ground wire on wood poles does more harm than it does good.

C. P. Steinmetz: The great value of Mr. Creighton's paper, in my opinion, consists in the very complete review and discussion of the function of the overhead ground-wire. While I thoroughly agree with all the facts brought out by him, I am sorry to say that I must somewhat disagree with the conclusions drawn therefrom.

I am fully convinced that the overhead ground-wire, when properly installed in a transmission system, is a most effective and a most valuable protective device.

I believe it is necessary to protect a station by adequate lightning arresters, and the failure to install lightning protection at the station is economically inexcusable. Nevertheless, if I were given the choice between the use of the overhead ground-wire, or the use of lightning arresters in the station without the overhead ground-wire, I would rather take my chances with the overhead ground-wire and no lightning protection in the station than to attempt to run without overhead ground-wire with all the lightning protection of the station that it would be possible to give, although neither of these plans is economically defensible, but both, ground-wire and lightning arresters, in my opinion, are necessary and are supplementary to each other.

The advantage of the ground-wire is that its function is preventive, while that of the lightning arrester is merely curative. The ground-wire keeps the high-voltage disturbances out of the system, those disturbances which might enter from the outside, by lightning, etc., or originate in the system, while the lightning arrester discharges such disturbances as have entered the system. Theoretically, therefore, either should be sufficient by itself to protect the system. Unfortunately however, neither of the two is complete in its action. The overhead ground-wire does not completely keep out abnormal voltages, but the best we can expect is that it reduces the over voltage of the disturbance, which, entering the station has to be discharged by the lightning arrester.

Unfortunately, the lightning arrester must have a spark gap in series with the discharge circuit, which must be set for a voltage materially in excess of the line voltage, so as not to interfere with normal line operation, and this is a limitation of the protective value of the lightning arrester, and every discharge of the lightning arrester, to some extent, means a shock to the system, and therefore it is desirable to reduce the work put on the lightning arrester as much as possible by the overhead ground-wire, and so getting the higher safety resulting therefrom.

In my opinion the two most important functions of the overhead ground-wire are, first, that it reduces the voltage electrostatically induced in the transmission line as the result of the bound charge on the line, produced by the charge of the thundercloud, or electro-magnetically as direct induction from a lightning flash overhead. When calculating this effect we invariably get rather disappointing results, that is the total effect is not more than 20 to 40 per cent voltage reduction at the most, and my conclusion and that of other observers is rather that the protective value of the overhead ground-wire is materially more than would be indicated by the reduction of the voltage due to its use.

The explanation therefore seems to me the following: For some years I have studied the phenomenon of the thundercloud, and from whatever data I gathered, to get an idea of the actual voltage of the thundercloud and the lightning flash, its current value, etc., my conclusion rather is that in the average the voltages induced by the thundercloud in transmission circuits are not very materially above those which the transmission line insulation would stand momentarily. With many of the induced lightning disturbances not much above the disruptive strength of the line, the result would be that a moderate reduction of the lightning voltages such as given by the ground-wires, would very much increase the safety of the system, out of proportion to the percentage of reduction, especially as not only the voltage, but also its duration is reduced by the ground-wire.

Thus it may be that a reduction of the lightning voltage by 30 or 40 per cent would, in view of the time lag of the circuit insulation, reduce the number of failures perhaps by 80 or 90 per cent, depending on conditions.

The second protective action of the ground-wire is its damping effect on any wave or other disturbance traveling along the line, by its action as a short-circuited secondary. The ground-wire must consume considerable of the energy of a traveling wave in the transmission line, and thus greatly increase the energy dissipation of the traveling wave, especially when it is considered that most of these ground-wires are steel cables, which have a large high-frequency resistance.

The result hereof would be that when using a ground-wire, only those disturbances, atmospheric and otherwise, which originated near the station, would reach the station with serious amplitude and dangerous voltage, but anything happening further out on the line would be sufficiently dissipated, or reduced in intensity, that when it reaches the station it is of negligible magnitude. I believe in this consists one of the main protective values of the overhead ground-wire, that it practically frees the station from any serious disturbance which occurs in the line at a considerable distance from the station, and requires the consideration only of those disturbances which occur nearer to the station, which are of a rather lesser number.

There also would be a certain action resulting from the energy dissipation which protects against the line building up standing waves or cumulative oscillation by arcing grounds, etc., in the transmission wires. That, however, is probably not of such great value, because the resistance of the transmission wire, is usually sufficiently high to limit the building up of a stationary wave. It is only in very high-power circuits where the line resistance is very low that there may be some danger of the building up of destructive oscillations. The two main features, in my opinion, are the screening effect tending to keep disturbances out, and the energy consumption rapidly dissipating disturbances, and these fully justify a properly installed overhead ground-wire in long distance transmission circuits.

W. S. Jones: In a paper presented at the meeting of the Institute at Washington, D. C. in 1914, Mr. L. A. DeBlois stated certain conclusions which were determined as a result of tests made by him in connection with the investigation of lightning protection for buildings. These conclusions appear to be pertinent to the subject under discussion and are quoted as follows:

"(a) All conducting surfaces not thoroughly grounded, when exposed to the influence of a charged cloud immediately overhead, acquire a potential against ground which increases with the height of the conducting surface above ground.

(b) A difference of potential will exist between all conducting surfaces not bearing the same average spacial relation in the electrostatic field to ground or to nearby grounded objects. Such average spacial relation is determined by their shape and size as well as distance from ground or grounded objects.

(c) Conducting surfaces in a vertical plane which would acquire practically no potential from their position in the electrostatic field may acquire a charge from the influence of adjacent objects.

(d) The grounding of a conducting surface generally increases the danger of sparks from adjacent non-grounded surfaces.

(e) Interconnecting adjacent conducting surfaces can prevent differences of potential between them but may increase the tendency of the lowest surface (relative to ground) to arc to ground.

(f) Discharges tend to take the shortest path, and large surfaces in the horizontal plane should be interconnected or grounded at more than one point.

(g) A grounded roof acts as shield for objects beneath it and even when poorly grounded diminishes the potential between them, but potentials can be introduced below it by conductors which extend inward from the outside, provided they are of sufficient capacity.

(h) Secondary discharges may occur from the sudden charge of an overhead cloud or from its discharge. The discharge in any case follows the natural frequency of the circuit and consequently may become oscillatory, though this condition is improbable in the ordinary interior apparatus, excepting only electrical equipment.

(i) The effect of adjacent lightning rods is to diminish the intensity of secondary effects, though for outside rods of reasonable height and spacing, the 'secondary static protective-ratio' is practically inconsiderable."

If these conclusions still hold true, and I believe that they do, the overhead grounded wire does not adequately safeguard the line against lightning on account of the induced secondary effects and the reluctance, on the part of a lightning discharge, to follow horizontally along an aerial conductor.

I believe that in such cases, where overhead grounded wires are used, a much more effective and satisfactory arrangement would be to provide a grounded aerial point at each pole were it practicable to extend the point to its proper height. This, however, appears to be a problem from a mechanical standpoint.

It is my opinion that the only effective means of protection against lightning and surge disturbances is the use of electrolytic arresters, or others equally as sensitive and as efficient, at frequent points along the line.

R. H. Marvin: This paper performs a valuable purpose in pointing out that before deciding either for or against the ground wire, that consideration must be given to the functions it is supposed to perform and the need for so doing.

There are few subjects on which experimental data are so scanty, difficult to obtain and to interpret when found.

In the case of wood pole lines it would appear that not enough importance had been attached to the effect of the high resistance of the pole. It is generally admitted, that with the possible exception of a direct stroke, the actual lightning discharge over the surface of an insulator is harmless. The damage is done by the dynamic or power arc which follows it. It is common practise in the laboratory to use high resistances in series with sphere gaps. The resistance does not effect the break-down voltage but does prevent a heavy current and injury to the spheres. Another good illustration is the horn gap arrester with high resistance. The value of such arresters is debatable, but its strongest enemies will admit that it does protect itself. This is well brought out in the recent "Questionnaire on Lightning Arresters" where one reply after describing the destruction of a modern type of arrester states, "I am positive that a water barrel horn gap style of arrester, as above suggested, would not have been injured."

The wooden pole gives this important feature of a high resistance between each insulator and the ground. There is not much known about high-voltage arcs, but it is probable that they follow the same general principles as the shorter low-voltage arcs. If this is so it can be shown that for any given arc length and pole resistance there is a definite minimum voltage necessary to maintain an arc. If the voltage is below this value, the arc cannot hold. It is probable that in many cases insulators on wood pole lines without ground wires flash-over from lightning, but owing to the high resistance of the pole no arc forms and no damage results. The particular point I would bring out is that it is not so much the induced lightning discharge we wish to prevent or avoid, but the destructive effects of the dynamic power arc.

This action is confirmed by several cases which have come under my observation. In the first instance, a 33,000-volt line with wood poles, metal arms and overhead ground wire gave excessive trouble from flash-overs. By mounting the ground wire on insulators and bringing the ground connection off in such a way as not to ground the metal arms, the trouble disappeared. Another 33,000-volt system having also metal arms on wood poles experienced numerous flash-overs and shut-downs on the parts having a ground wire, but none on a short section where the ground wire had been omitted.

E. E. F. Creighton: Engineers of transmission systems will note, with respect, the foregoing comments of the able discussers of this incomplete presentation on overhead grounded wires. There are convincing opinions expressed both for and against the use of the grounded wire. We must, for the present, let the situation stand. Briefly summarized, there are places where the use of the overhead grounded wire is good practise. On the contrary, there are other conditions of line construction where the expense of the overhead grounded wire is an economic waste. This is the particular point the author wishes to stress. In between these extremes there is a range of middle ground where the use or absence of the grounded wire becomes a special problem.

The present state of knowledge of this problem is admirably brought to mind by choosing an expression from Mr. Lewis's and Mr. Marvin's discussions respectively, and placing these expressions in juxtaposition. "It is their (the operators') *belief*, based on experience, that overhead grounded wires afford considerable protection from lightning disturbances." "There are few subjects on which *experimental data* are so scanty, difficult to obtain, and, when found, to interpret."

There are developments now under way which, when available, will help to crystallize more definitely the practise in the use of overhead grounded wires.

Wave Form and Amplification of Corona Discharge

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Review of the Subject. *Corona forms on a round wire or cable when the voltage is raised to such a point that the voltage gradient near the wire is sufficiently high to break down the insulating properties of the air. The larger the wire the higher the voltage to cause corona. The corona is luminous and ionizes the air, giving it electrical conductivity; thus corona has the effect of giving the conductor a larger diameter; and since a higher voltage is required for corona on a larger wire, a state of equilibrium is reached and corona is an equilibrium phenomenon not necessarily attended by spark-over.*

Since corona causes conductivity it is a cause of leakage and consequently of loss of power. It also increases temperature and decomposes the air into chemical constituents which are harmful to insulation. Engineers therefore have usually regarded corona as a dangerous phenomenon and one to be avoided by proper design. Transmission lines, for example, for the most part are designed so that their operating voltage is well below that at which corona would be formed on the conductors.

Two suggestions have been made to make use of the properties of corona. The first is as a protective device for transmission lines. Since the corona is conducting and dissipates energy, it has been proposed to operate transmission lines relatively close to the corona-forming voltage. When abnormal rises of voltage due to lightning or other causes occur, corona begins, the air becomes conducting, and the high voltage is relieved. The exact value of corona in this connection is not known, although there is some evidence that it acts in the manner described.

A second use of the corona, suggested by one of the authors of the present paper, is that it be used as a method for measurement of the crest values of high alternating voltages. The corona begins at a sharply marked definite value of voltage, and the laws governing the value are now well-known. The corona voltmeter is an instrument for detecting, either by the sound or by the conductivity of the air occasioned by corona, the exact voltage at which corona begins. The value of the voltage is given in terms of the dimensions of the instrument and the pressure and temperature of the air. The instrument has been described in two earlier papers, in which it is shown that the measurements of voltage with the corona voltmeter are more accurate than by any other method and that the instrument has several other advantages over methods at present in use. The present paper deals with methods for increasing the sensitivity of the corona voltmeter and for adapting the ordinary telephone receiver and standard portable instruments as indicators of the first appearance of corona. The corona discharge current is rectified and also amplified by means of hot cathode tubes. Incidentally the experiments on rectification included a study of the wave form of the discharge due to the alternating corona. It was also found that the sound due to the corona could be amplified so that the first appearance of corona would be indicated on a loud-speaking telephone.

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I. INTRODUCTION

THE high-voltgage corona appears at a sharply marked definite value of voltage of a clean round wire. This fact is made use of in the corona voltmeter, the law of corona as affected also by temperature and pressure being now known to a high degree of accuracy. The instrument appears to offer the most accurate method for determining crest values of high alternating voltages.

In addition to the method of visual observation, which is relatively inconvenient, two methods have been used in the corona voltmeter for detecting the first appearance of corona, (a) the telephone, and (b) the continuous-current galvanometer. Both of these devices indicated the first appearance of corona with a high degree of accuracy. Under laboratory conditions either may be used with satisfaction, the telephone being somewhat simpler, and useful for detecting occasional local sparking due to surface imperfections of the corona wire. However, the total volume of

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corona discharge produces a relatively small current, so a sensitive galvanometer is necessary, more sensitive than can be had in a readily portable type, and requiring usually a telescope and scale. Consequently some inconvenience is occasioned if the voltmeter is to be moved from place to place. Moreover the sound of the corona in the telephone, while clear and sharp in a quiet room, is easily masked by other extraneous noises. It is desirable therefore to develop methods for observing the first appearance of corona on the usual type of portable instrument with direct-reading scale, and also by means of a loud-speaking telephone. Both these things have been accomplished in the experiments described below, thanks to the rectifying and amplifying properties of the three-electrode vacuum tube. In addition some interesting curves showing the wave form of corona discharge have been obtained.

II. Apparatus and Method

The essential elements of the galvanometer method of detecting corona are shown in Fig. 1, in which *C*, the perforated cylinder in the corona voltmeter, is connected to ground, and the corona wire *F* is placed in the center of the cylinder. *D* is a surrounding cylinder only slightly larger in diameter than *C*, from which it is carefully insulated. When corona appears on the central rod *F* the surrounding air is copiously ionized and this ionization extends through the perforations to the space between the cylinders *C* and *D*, which thus becomes highly conducting, resulting in a deflection of the galvanometer *G*.

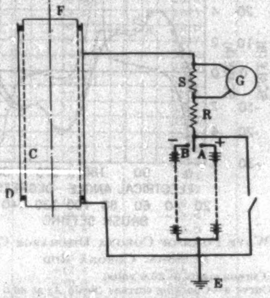


Fig. 1—The Galvanometer as Detector of Corona

The present experiments were all conducted with the corona discharge on a nickel-plated steel rod 0.289 cm. (0.188 in.) in diameter. The sensitive d'Arsonval galvanometer used is of wall type and has an undamped sensitivity of 1280 megohms; when critically damped with a shunt of 3400 ohms the sensitivity is 428 megohms. The resistance *R*, Fig. 1, of 50,000 ohms was put in series to protect the galvanometer from possible short circuit in the corona voltmeter. The potential of the battery between galvanometer and ground was plus or minus 115 volts.

The length of the cylinder *D* was 60.95 cm., its diameter 24.67 cm., and its space separation from the cylinder *C* 0.317 cm.

The curves in Fig. 2 were taken with the corona rod, 0.289 cm. diameter and plotted with galvanometer deflections in centimeters as ordinates, and transformer tertiary coil volts as abscissa. (See Fig. 3). The ratio of transformation of the high-tension transformer was such that 120 volts on the tertiary coil corresponded to 100,000 volts at the high-voltage terminals. Three curves were taken at atmospheric pressure, one with the electrode *D* of Fig. 1 at 115 volts positive, one at 115 volts negative, and one at ground potential as shown in Fig. 2.

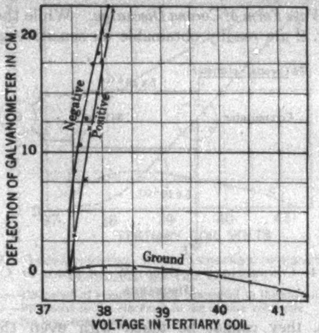


Fig. 2—Galvanometer as Detector of Corona
(0.188 in. = 0.478 cm. diameter rod)
Atmospheric pressure.

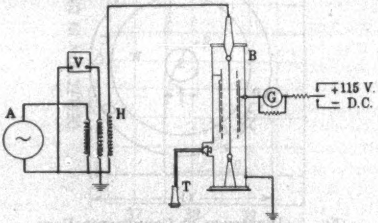


Fig. 3—Principal Connections
A—Alternator.
H—High-tension transformer.
V—Tertiary coil voltmeter.
B—Corona voltmeter.
G—D'Arsonval galvanometer.
T—Telephone receiver.

It is to be noted that negative potential on the electrode *D* is best for the detection of the first presence of corona, in that the curve rises most sharply. The greater sensitivity of the negative electrode is obviously due to the fact that corona formation or ionization of the air occurs first due to the motion of the negative electron. The acceleration of the electron is greatest when it is moving toward the positively charged corona conductor. Under these circumstances the positive ions, as products of the process of ionization, are repelled and therefore give maximum current in the galvanometer circuit of Fig. 1 when the electrode *D* is negative.

III. Galvanometer with Rectifying Valve

a. Wave Form of Corona Discharge. While the curves of Fig. 2 are readily obtainable on sensitive galvanometers, they cannot be taken with even the most sensitive types of direct-reading portable instrument. In considering possible ways of using the discharge with satisfaction on a less sensitive type of instrument it is to be noted at once that in the arrangement of Fig. 1 the deflection of the d'Arsonval galvanometer is proportional to the difference of the mean values of the corona discharge on the positive and negative sides of the wave form. The deflection due to the discharge must therefore be largely due to some difference in the heights of the peaks in the positive and negative sides of the discharge current. It is evident therefore that elimination of one-half of the discharge current curve will greatly increase the net unidirectional current in the galvanometer circuit. This can be accomplished either with a synchronous commutator used as suppressor, or more conveniently still, by means of a rectifying vacuum tube. The whole question of the difference between the volume of discharge on the positive and negative sides of the voltage waves is one of great interest. It therefore seemed desirable, from the standpoint of the purpose of the experiments and also from that of the interest of the phenomenon itself, to take a series of wave forms of the corona discharge current.

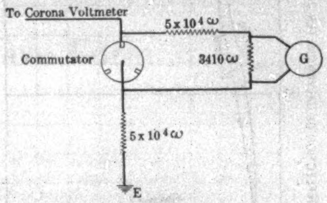


Fig. 4—Connections to Study Wave Form of Corona Discharge

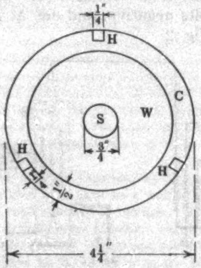


Fig. 5—Dimensions of Commutator Used

C—Copper disk,
H—Insulator (hard rubber),
W—Wooden block,
S—Shaft.
Thickness of copper disk: 1/8 inch.

For this purpose a special synchronous commutator was mounted on the shaft of the alternator furnishing the high voltage. In Fig. 4 the commutator was put in shunt to the galvanometer and the discharge current was short-circuited through each full cycle, except for one very short interval. The commutator, Fig. 5, was made of a copper disk, 4¼ in. diameter, with three slots of ¼-in. width filled with hard rubbed placed at intervals of 120 deg., corresponding to half the number of poles of the alternator, and so each giving open circuit at the same position on the wave form. The commutator was insulated from the shaft. Three copper brushes were attached at intervals of 30 deg. on the movable wooden disk; the two outer brushes were connected together to keep continuous contact to the copper disk, and under the middle one the open circuit was given by the three slots on the commutator.

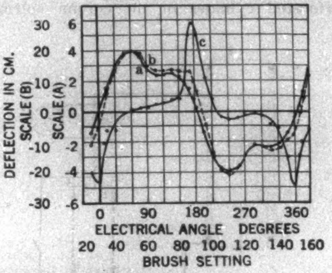


Fig. 6—Wave Form of Corona Discharge Current on 0.188-in. Corona Rod

(Corona starts at 36.6 volts)
Curve *a*—Charging current (Scale *A*) at 36.5 volts,
Curve *b*—Deformed current (Scale *A*) at 36.6 volts,
Curve *c*—Corona discharge current (Scale *B*)

First, the brush setting was observed corresponding to the maximum value of voltage on the corona wire by shifting the brush to find the point of no charging current in the galvanometer, and it was found to be 30 deg. on the fixed disk, calibrated 360 deg. on the whole circle.

Two wave forms of the currents through the galvanometer circuit were observed for voltages below and above corona formation; the difference of these wave forms must be the wave form of corona discharge. The wave form observed just before the start of corona is the charging current through electrode *D* and the wave form observed just after the start of corona is the superposition of charging current and corona discharge current.

The observations were taken at atmospheric pressure of 74.77 cm. and room temperature of 18.2 deg. cent. on the corona wire of 0.289-cm. diameter. Readings are shown in Table I; the curves in Fig. 6 are plotted from the same observations; the positive direction of current was from the electrode *D* to ground (Fig. 1.).

From the curves it may be seen that the corona discharge current is of alternating form with a rather peaked shape for each half cycle, but the value of the positive peak is a little higher than that of the negative and this is the reason why the negative electrode is more effective for detecting corona.

TABLE I.
Wave Form of Corona Discharge

Brush setting in degrees	Galvanometer deflections in cm. Before corona	After corona	Corona discharge
25	−6.5	−10.5	−4.0
30	.3	− 4.5	−4.8
35	7.6	6.4	−1.2
40	15.0	13.8	−1.2
45	19.5	19.3	−0.2
50	20.5	20.6	0.1
55	18.5	18.7	0.2
60	14.0	14.2	0.2
65	11.7	12.2	0.5
70	12.1	12.7	0.6
75	12.5	13.3	0.8
80	11.3	12.1	0.8
82.5	9.2	12.0	1.8
85	7.1	12.1	5.0
87.5	4.2	10.1	5.9
90	1.3	6.3	5.0
92.5	− 3.0	1.1	4.1
95	− 6.7	− 4.4	2.3
97.5	−10.9	− 9.8	1.1
100	−13.9	−13.0	0.9
105	−18.8	−19.0	−0.2
110	−19.9	−20.4	−0.5
115	−18.1	−18.5	−0.4
120	−13.4	−13.7	−0.3
125	−10.5	−10.6	−0.1
130	−11.1	−11.3	−0.2
135	−11.8	−12.7	−0.9
140	−10.6	−11.7	−1.1
142.5	− 8.5	− 9.9	−1.4
145	− 6.6	− 9.5	−2.9
147.5	− 4.5	− 8.7	−4.2
150	− 1.2	− 6.1	−4.9
152.5	2.5	− 0.3	−2.8
155	6.8	4.8	−2.0
160	14.6	13.5	−1.1

b. Rectifying Valve in Detecting Circuit. If we choke off one of the half waves shown in curve *C* of Fig. 6 we have at once a great increase of unidirectional current in the detecting galvanometer circuit. As stated above, the most convenient way of accomplishing this is the rectifying tube or valve of "kenotron" or similar type, which as is well-known passes current from a plate electrode to a heated filament, but completely chokes current from the filament to the plate.

Placing the valve between the galvanometer and the electrode in the corona voltmeter, Fig. 1, we observe at once a great difference in the sensitivities as between the two methods of connecting the valve in the circuit, *i. e.*, (1) the filament of the valve connected to the electrode and the plate to the galvanometer, and (2) the filament to the galvanometer and the plate to the electrode.

In Fig. 7 three curves correspond to the three cases, (a) filament connected to the galvanometer, (b) filament to the electrode, and (c) no valve being used. In each case no continuous potential was used, the galvanometer being connected directly to ground through the high resistance *R*, Fig. 1.

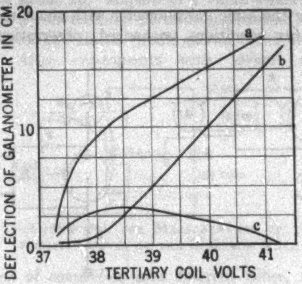


FIG. 7—GALVANOMETER WITH KENOTRON WITHOUT ANY POTENTIAL ON THE CIRCUIT

Curve *a*—Filament of kenotron being connected to the galvanometer.
Curve *b*—Filament to the electrode in the corona voltmeter.
Curve *c*—No kenotron used.

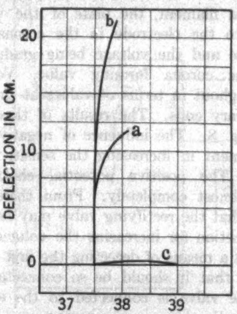
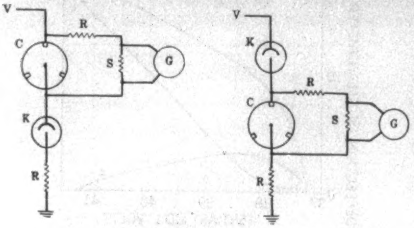


FIG. 8—GALVANOMETER WITH RECTIFYING VALVE POTENTIAL APPLIED ON THE FILAMENT

(Plate of valve connected to the electrode in the corona voltmeter)
Curve *a*—No potential on the filament, this corresponds to the curve (a) in Fig. 7.
Curve *b*—Negative potential on the filament.
Curve *c*—Positive potential on the filament.

From these results it may be said that the valve with its plate connected to the electrode gives the maximum volume of corona discharge current. This is in agreement with the condition of greatest sensitivity when the valve is not used, namely, negative electrode

D, or current from electrode to ground. For greater sensitivity we add negative potential of 115 volts on the filament through galvanometer and high resistance by means of a battery of cells. With positive potential on the filament no current was detected, as is to be expected.



FIGS. 9 AND 10—CONNECTIONS SHOWING THE TWO POSITIONS OF KENOTRON

C—Commutator.
K—Kenotron.
G—Galvanometer.
S—Shunt resistance (3410 ohms).
R—Resistances (5×10^4 ohms each).
V—Corona voltmeter.

In connection Fig. 10 we found no charging current on the wave form of corona discharge current.

Using the same galvanometer with shunt resistance and other conditions unchanged, observations were taken of galvanometer deflections corresponding to (a) no potential on valve filament, (b) negative potential 115 volts on valve filament, and (c) positive potential 115 volts on filament, the plate of the valve being connected to the electrode in the corona voltmeter in each case and the voltage being gradually raised through the corona forming value. Voltages are given throughout in terms of values at the terminals of the tertiary coils. The results of these tests are given in Fig. 8. The influence of negative potential on the filament in increasing the sensitivity is very noticeable. The positive potential chokes off the discharge almost completely. From these results it is obvious that the rectifying valve may be used with great satisfaction for increasing the volume of corona discharge as a means of detecting the first presence of corona and that it should be so connected that the plate of the valve is connected to the electrode in the corona voltmeter.

c. Portable Instrument in Place of d'Arsonval Galvanometer. Although the volume of the discharge current is greatly increased by the methods described above, it was found to be not yet sufficient to give satisfactory indications on a portable type of instrument. Tests of this question were made using a Siemens and Halske needle galvanometer having 25 divisions of scale on each side of a central zero, and each division corresponding to 10^{-6} ampere. The resistance of the instrument is 100 ohms.

Using this needle galvanometer with shunt of 9000 ohms in place of the d'Arsonval galvanometer of the earliest experiments, we found a deflection of only 1½ divisions for a voltage 6 per cent above corona-forming value. Ordinarily this excess voltage would give deflections well off the scale using the most sensitive wall-type instrument. In these experiments the filament of the valve was connected through the instrument to the negative terminal of a 115-volt instrument, this being the most sensitive method of connection, as described above.

In view of these results it will be seen that while the rectifying valve has given a great increase in the volume of discharge, this increase is not yet sufficient to permit the use of the common type of portable instrument. If this type of instrument is to be used, some form of amplification of the discharge current must be used. This amplification was accomplished by the use of three-electrode amplifying tubes in the experiments described below.

d. Wave Form of the Rectified Corona Discharge Current. Before applying the usual methods of amplification to the corona discharge current it is important that the rectified corona discharge shall have no reverse current, that is that it shall be strictly unidirectional. Elimination of reverse currents is necessary since the rectifying valve and also the amplifying tube may be overloaded by them and so prevent the amplification of the unidirectional component. For these reasons we investigated the wave form of the rectified current by means of the synchronous commutator, as described above. At first we found large values of charging current in the wave form, these being induced currents arising in the circuit between the galvanometer and ground, and due to the alternating static field. In these measurements the galvanometer was connected directly to the electrode in the corona voltmeter and the valve between the galvanometer and ground, as shown in Fig. 9. After shortening the connections between all parts and changing the positions of the valve and the galvanometer to those shown in Fig. 10, we finally obtained strictly unidirectional current of very irregular wave forms.

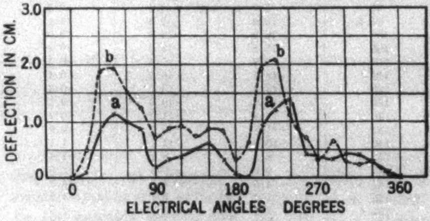


FIG. 11—WAVE FORMS OF RECTIFIED CORONA DISCHARGE CURRENTS BY THE KENOTRON

Curve *a*—No potential applied on the filament of the kenotron.
Curve *b*—Negative potential applied on the filament of the kenotron through the galvanometer and the high resistance.

The two curves in Fig. 11 were measured by the commutator method described above, the plate of the valve being connected directly to the electrode in the corona voltmeter. First one side of the galvanometer was grounded through the high resistance R, and next negative potential of 115 volts was applied to the filament through the galvanometer and high resistance.

The irregularity of the wave forms shown in Fig. 11 is in some measure due to the continuously changing thermoelectric electromotive force at the brush contacts which is not sufficiently eliminated by the high resistance in series in the galvanometer circuit. (See Fig. 4.) This thermal electromotive force was further eliminated in its effect on the current to be measured by taking the difference of right and left galvanometer deflections both before and after starting corona. It is probable that the elimination of this effect is not complete and that therefore the curves shown in Fig. 11 are not an exact reproduction of the shape of the corona discharge. They must however approximate it very closely and they show clearly that there is no reverse element in the rectified current. It is sufficient for amplification that there be no reverse current and consequently these experiments were next undertaken.

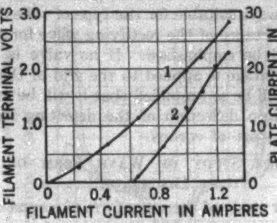


Fig. 12

Curve 1—Filament terminal volts,
Curve 2—Plate current.

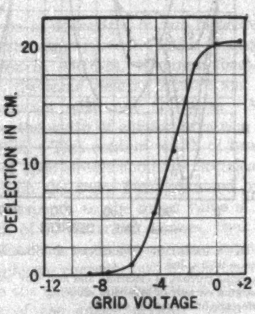


Fig. 13—Plate Current

IV. Amplification of Corona Discharge Current

a. Characteristic Curves of the Electron Tube. The problem presented is to amplify the unidirectional pulsating current from electrode D with an average value of about 10^{-7} ampere to a value which may be read on a conveniently portable instrument, such as the Siemens and Halske needle galvanometer, described above. After experiments with several different methods of connection and different tubes, the connections of Fig. 15 were found to be most suitable for our purpose.

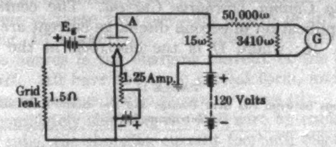


Fig. 14—Connection for Measurements of Characteristic Curves of the Electron Tube

One 102-A Western electron tube was used and its characteristic curves were studied. The relation between plate current and filament current with no grid voltage and also the relation between plate current and grid voltage with constant filament current were taken. The curves of Figs. 12 and 13 were taken with a d'Arsonval galvanometer in the plate circuit and with 120 volts on the plate. Fig. 14 shows the method of measuring the relation between plate current and grid voltage. The relation of filament current and plate current is obtained with slight modifications of the connections as shown. The grid leak of 1.5 megohms and a different location of the ground connection is required for the amplification of the corona discharge current. (See Fig. 15). In these experiments, owing

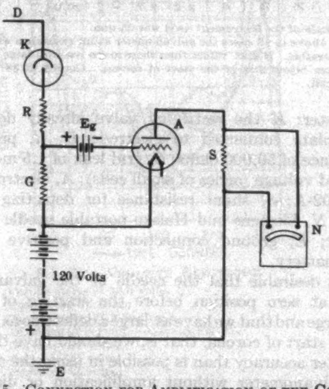


Fig. 15—Connection for Amplification of the Corona Discharge Current

to its high sensitivity the galvanometer was equipped with a shunt, as shown.

From the curve of Fig. 15 it is seen that the grid voltage must be about 8 volts in order to secure zero deflection in the connection of Fig. 15. With the start of corona and current over the resistance *G*, we may expect a sharp increase in plate current, that is to say, amplification.

b. Connection and Operation of the Amplifier for Increasing Corona Discharge Current. The connections for amplification of corona discharge current are shown in Fig. 15; where *D* is the electrode in the corona voltmeter; *K* the rectifying valve already described, with plate connected to electrode *D*; *R*, protective resistance of 50,000 ohms; *G*, grid leak of 1.5 megohms; E_g, grid voltage (series of small cells); *A*, electrode tube No. 102-A; *S*, shunt resistance for detecting instrument; *N*, Siemens and Halske portable needle galvanometer; *E*, ground connection and positive side of plate battery.

TABLE II.

Relations between the Grid Voltage and the Shunt Resistance of the Galvanometer.

Grid Voltage,	0.0	1.48	2.97	4.47	5.94	5.94	7.43	7.43	8.85	8.85
Shunt Resist. in ohms,	1.0	1.0	1.0	1.0	1.0	10.	10.	100.	100.	1000.
Tertiary Coil Volts,	Deflections in mm.									
22.0	7.8	7.7	5.5	2.0	0.8	5.0	1.0	2.8	0.5	0.7
38.1	7.8	7.7	5.5	2.0	0.8	5.0	1.0	3.2	0.5	0.7
38.2	No change	No change	No change	2.8	2.0	18.7	10.5	Off scale	24.5	Off scale
38.5				2.9	2.2	20.7	12.8		Off scale	
39.0				3.0	2.4	23.0	14.0			
39.5				3.1	2.6	Off scale	16.8			
40.0				3.2	2.7		20.0			

*Full scale of the instrument used was 25 mm.

In the above in all cases the galvanometer shunt resistance was made as high as possible. Higher values than those given result in large deflections at voltages below that of the start of corona. Corona at 38.2 volts on tertiary coil.

It is desirable that the needle of the galvanometer stand at zero position before the starting of corona discharge and that we have as large a deflection as possible on the start of corona, that is, we should have the same or better accuracy than is possible in using the d'Arsonval galvanometer without amplification or discharge. We were able to obtain this condition very closely after many trials by changing the value of the shunt resistance *R* and the value of the grid voltage E_g. We were able to obtain such conditions that the initial deflection of the galvanometer was less than one millimeter before the starting of corona, and immediately off the scale when corona begins. The process of obtaining this condition is clearly seen in Table II, where the relations between the shunt resistance, values of grid voltage, and initial deflection are given. The value of the grid leak was also varied from 50,000 ohms to 2 megohms, and it was found that 1.5 megohms grid leak gives most satisfactory results in amplification.

From the above results the following are the best values for amplification: Grid voltage, 8 to 9 volts; shunt resistance, 100 to 1000 ohms; grid leak, 1.5 to 2 megohms. Obviously the value of shunt resistance pertains only to the instrument used in these experiments, but the values of grid voltage and grid leak are always suitable for the type of tube described.

The importance of the rectifying valve for amplification should be emphasized. If no valve is used, alternating voltage is applied to the grid of the electron tube and will be so amplified that it will be impossible to secure zero deflection of the detecting instrument before the start of corona.

V. FURTHER STUDY OF WAVE FORM OF CORONA DISCHARGE

A further study of the wave form of corona discharge has been made and in this the value of the discharge current has been carried far above that in the immediate neighborhood of the starting of corona.

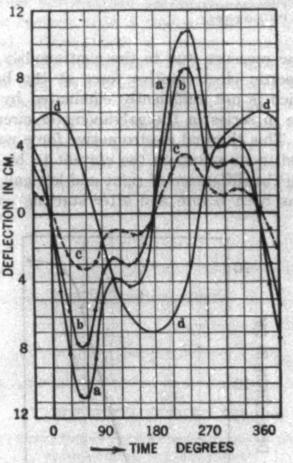


FIG. 16—CHARGING CURRENTS AT 36.5 VOLTS
(Corona starts at 37.2 volts)
Curve *a*—Charging current of electrode and lead wire together,
Curve *b*—Charging current of lead wire alone,
Curve *c*—Difference of curves (a) and (b),
Curve *d*—Wave form of voltage.

a. Improvement of Synchronous Commutator. As shown in Fig. 5, the width of each slot filled with hard rubber corresponds to 20.2 electric degrees. If the middle brush, under which the open circuit is given by each slot, has no thickness, then the duration of open circuit must correspond to the interval of 20.2 electrical degrees and the deflection of the galvanometer is proportional to the mean value of the wave form during that interval. But obviously it has a certain contact area which will shorten the duration of open circuit, and the amount of this shortened period must correspond to the width of the brush contact area.

In the case of the observation of the curves shown in Figs. 6 and 11, two 0.005-in. copper strips were used as the middle brush. The effect of the wearing of contact surface and different pressures on the brush was noted in the difference of deflections in two measurements of wave form of the same current. As a consequence we used one sheet of 0.016-in. thickness because it is easier to keep the same wearing surface and the same pressure of contact with one thickness. After sufficient wearing the width of contact area was measured as about 1/32-in. This contact width of brush makes the duration of open circuit about 16 electrical degrees, and the point on the wave form obtained by shifting this brush corresponds to the mean value of the wave form of width of 16 electrical degrees, thus the wave form as obtained by us is not an exact representation of corona discharge current, but is approximate only, each point on the curves representing a width of about 4.5 per cent of the entire period. With this commutator Figs. 16 to 19 were taken.

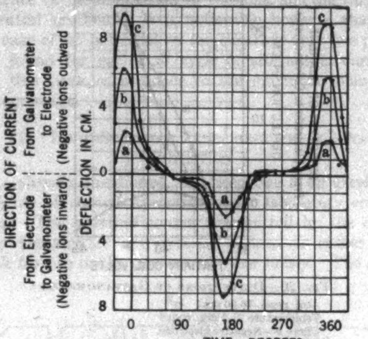


Fig. 17—No Voltage on Electrode

Corona starts at 36.7 volts,
Atm. press. 75.77 cm.
Temperature, 20.8 deg. cent.
Curve *a*—37 volts,
Curve *b*—41 volts,
Curve *c*—45 volts.

b. Galvanometer used. In order to obtain rapid readings of the two deflections on the two sides of zero, for the elimination of the thermoelectric electromotive forces on the commutator, a galvanometer of short period was used, sensitivity 1085 megohms undamped, and a period of 13.8 seconds. When critically damped with 1900 ohms the time required for the deflection to fall to zero from 12 cm. was 13.6 seconds.

c. Shielding of Lead Wire between Electrode D and the Galvanometer. Careful electrostatic screening of all connections and instruments is necessary in measurements of the small values of current in the connection to electrode *D*. At first electrostatic induction between the high-tension conductor of the voltmeter and the lead wire from the electrode to the screened observation room was found to be comparatively large. Working below the starting voltage of corona we measured the charging currents, (a) of electrode inside and lead wire outside together, and (b) lead wire alone by disconnecting at the outlet of the corona voltmeter. The wave forms in these two cases are shown in (a) and (b) of Fig. 16 respectively. The difference between these two curves is the charging current of the electrode itself. All have the same typical form, and the wave form of voltage is also shown in curve (d).

After completely shielding the lead wire by enclosing in metal tube, the charging current for both electrode *D* and lead wire when connected together is practically coincident with the curve (c) of Fig. 16, showing the elimination of exterior electrostatic induction.

It is not possible to eliminate completely the charging current of the electrode *D*, owing to the holes in the grounded cylinder of the voltmeter. These holes are essential to its principle of operation. Thus the wave form at voltage just above the start of corona is the superposition of the electrode charging current and the corona discharge.

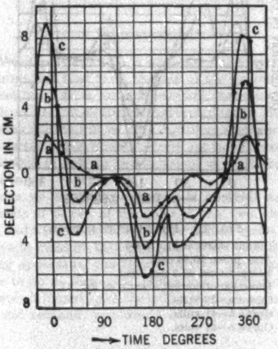


Fig. 18—Negative Electrode

Corona starts at 36.5 volts.
Atm. press. 75.47 cm.
Temperature, 25.2 deg. cent.
Direction of current:—same as Fig. 17.
Curve *a*—37 volts,
Curve *b*—41 volts,
Curve *c*—45 volts.

d. Wave Forms of Corona Discharge Current with 0.289-Cm. Nickel Steel Rod. With the speed of the alternator maintained constant by a tuning-fork speed-control device and by shifting the commutator brush in the direction of rotation of the alternator, wave forms were taken for various conditions of corona discharge. Twelve points were taken on each half wave. We record three sets of wave forms as follows: (1) For no continuous potential between electrode and ground, (2) for negative electrode, and (3) for positive electrode. Each set consists of three curves, one taken just above the corona starting voltage, and two at values considerably higher. They are shown in Figs. 16 to 19.

It was possible to take only one set of curves in any one day and consequently different values of starting voltages of corona are shown. The charging current of the electrode for a voltage just below the starting of corona was taken in each case. The fact that the values of this charging current were equal in all three cases is a check on the satisfactory condition of the commutator and brushes.

In all of the curves (Figs. 16 to 19) 0 deg. and 180 deg. of electrical angle on the commutator scale were fixed by the position of zero charging current, corresponding to the maximum points on the voltage wave. The wave form of the voltage of the high-tension side of the transformer was measured by means of an air condenser, and is shown in Fig. 16. As the true wave form of corona discharge measured by the present method is the difference of the two wave forms below and above the critical value of voltage, it appears to be quite accurate only for voltage a small value above the corona starting value. For higher voltages, however, it is not correct to take the difference between, the total current and the charging current as measured since the charging current itself becomes larger. This charging current is approximately proportional to the voltage except insofar as the capacity of the voltmeter may alter, due to the presence of corona. In the absence of definite knowledge on the magnitude of this alteration of capacity, the curves in Figs. 17, 18 and 19 were based on corrected values of the charging current for each voltage, assuming this charging current to be proportional to the voltage. All that may be said on this point at this time is that the shapes of the resulting curves indicate that a possible error on this account does not manifest itself in any serious change in the shapes of the curves. In Fig. 20, three curves are shown giving the net discharge currents under the conditions of Fig. 1. These curves are comparable with those of Fig. 2, except that they are taken with the d'Arsonval galvanometer used in the wave form experiments. The current read in these curves therefore is the algebraic sum of the positive and negative half waves of the discharge current. It is interesting to compare these curves with the wave forms of the currents under the corresponding conditions as shown in Figs. 17, 18 and 19. The deflection of the galvanometer in Fig. 20 without the use of commutator is proportional to the difference of the mean values of each half wave, and in the case of no potential on the electrode (Fig. 17) there is a slight difference between the two half waves, and this accounts for the relatively small deflection of the curve (*c*) in Fig. 20. In the case of negative electrode (Fig. 18) the predominating mean value of half wave can be seen clearly as that whose direction is from the electrode to the galvanometer. A similar predominating mean value with direction reversed can be seen as pertaining to the curve (*b*) of Fig. 20, and the curves of Fig. 19.

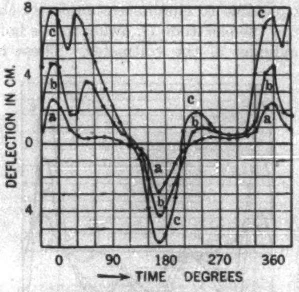


FIG. 19—POSITIVE ELECTRODE

Corona starts at 37.7 volts.
Atm. press. 76.86 cm.
Temperature, 21.2 deg. cent.
Direction of current:—same as Fig. 17.
Curve *a*—38 volts.
Curve *b*—41 volts.
Curve *c*—45 volts.

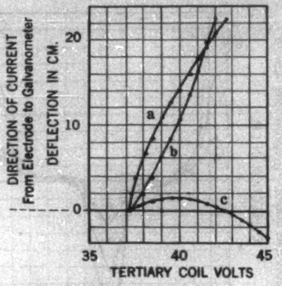


FIG. 20—DEFLECTIONS OF GALVANOMETER

Atm. press. 76.86 cm.
Temperature 21.2 deg. cent.
Curve *a*—Negative electrode.
Curve *b*—Positive electrode. (Reverse direction)
Curve *c*—No potential.

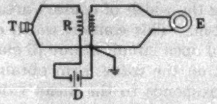


FIG. 21—STRAIGHT TELEPHONE CIRCUIT AS DETECTOR OF CORONA FORMATION

T—Telephone transmitter
R—Telephone repeating coil
D—Two dry batteries in series
E—Ordinal telephone receiver

We can offer no explanation of the very irregular shapes of the waves of discharge current when negative and positive potentials are used on the electrode. It is noticeable that one-half wave in each case has the characteristic single peaked form as given by Fig. 17. It is the reverse wave which has the broken shape. We can only point to the complicated condition of ionization between the rod and outer cylinders, as influenced by the varying time above ionizing voltage, the rate of recombination of the ions, and the varying potential gradient. It is noticeable however that in the case of no potential on the electrode only one peak was found for each half cycle of alternating current and this peak corresponds to the maximum point of voltage wave.

VI. LOUD-SPEAKING TELEPHONE FOR CORONA DETECTION

As already mentioned, the telephone is an excellent detector of corona formation under laboratory conditions. The sound of corona transmitted by the ordinary transmitter and receiver is however rather too weak for use in the presence of other noises. The connections using an ordinary transmitter, repeater, and receiver for use as detection are shown in Fig. 21. In order to obviate the disadvantage mentioned we have tried a loud-speaking telephone and have succeeded in greatly amplifying the sound of corona discharge. Many experiments and different types of connection were tried before a substantial amplification was obtained, but for brevity we give only the results and final method of connection. The greatest difficulty was found in separating the pure corona note from other noises which were also picked up and amplified in the loud speaker. The connections of Fig. 22 give a very satisfactory amplification, so that observations on the beginning of corona are readily possible at some distance from the loud speaker and in the presence of normal noises of a large laboratory, such as the operation of several other machines and the talking of individuals. One stage of amplification with a Weston 102-A tube was used, and other details are given in connection with Fig. 22.

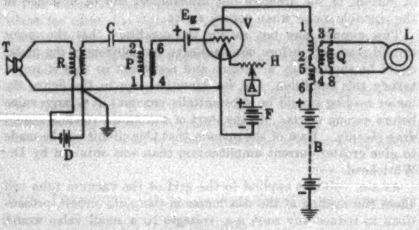


FIG. 22—AMPLIFIER OF THE SOUND OF CORONA FORMATION

D—Two dry batteries in series,
T—Telephone transmitter,
R—Ordinal telephone repeating coil,
C—Two condensers 2 μ. f. each in parallel,
P—Input transformer,
E_g—Grid voltage (1.5 volts),
V—Vacuum tube,
H—Wire resistance,
F—Filament battery (filament current:—about 1 ampere),
A—d-c. ammeter,
B—Plate battery 115 volts,
Q—Output transformer,
L—Loud-speaking telephone receiver.

While the results with the loud speaker are interesting, assuring the possibility of detecting corona formation and announcing it to several people at a distance, we believe that quite the same degree of accuracy of determination, if not better, can be obtained by a close-fitting head-piece, shutting out other noises, equipped with the ordinary telephone receiver. Under these circumstances extremely accurate indications of the first appearance of corona are possible.

Detailed description of the rectifying valves, speed-control device, commutators, and other equipment mentioned in this paper will be found in a paper entitled "The Corona Voltmeter, the Electric Strength of Air," by J. B. Whitehead and T. Isshiki, A. I. E. E. TRANSACTIONS 39, May 1920.

Discussion

J. H. Morecroft: There is only one point on which I can add anything and that is on the use of the vacuum tube as a voltage rectifier. It is an experimental instrument not used very much as yet by electrical engineers, but as Dr. Hull told us some time ago, it will be used by every engineer very soon. There are certain cases where voltages are to be measured where it is impossible to get the measurement without the use of the vacuum tube.

Sometimes we want measurements in a circuit having but a few millivolts of power, of the order of one, two, three, four or five volts, and a frequency of perhaps a million cycles per second. If you have to measure that kind of a circuit with the ordinary engineering apparatus, you throw up your hands and say it is impossible to do it, there is no indicating instrument which will respond, even if it used up all the millivolts there are in the circuit, and if it did respond, you would not know what the reading meant, because the errors at a million cycles would be excessive, and it would be necessary for you to have recourse to the newer devices, of which the vacuum tube is the most important.

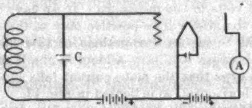


FIG. 1—SCHEME FOR MEASURING MAXIMUM VOLTAGE ACROSS CONDENSER C

Take an oscillating circuit with an unknown voltage across the condenser, and a frequency of, let us say, a million cycles, and measure the voltage. We might try to put a voltmeter across the condenser. If we did, the voltmeter would short-circuit the current, and we would have no voltage at all, so that evidently will not work. A scheme like this, however, will work. Put the grid of a vacuum tube as in Fig. 1, insert a biasing battery which makes the grid of the vacuum tube negative, and if the grid of the vacuum tube is made sufficiently negative, there will be no current going through the plate circuit. When this circuit is not excited, put on sufficient negative voltage, on the grid by means of the biasing battery so that the plate current is cut off, and then, if you start to excite the circuit, the grid will go up and down in potential, and as soon as it goes positive, a little bit more than the critical amount, as previously adjusted, then the grid, going positive, will allow a little bit of current to go through the plate circuit, and if the plate circuit instrument is sensitive enough, you can read it. The biasing battery must now have its voltage increased to reduce the plate current again to zero; the amount of increase in biasing voltage is the maximum value of the high-frequency voltage across *C*. In the case of corona you ordinarily have much more power available than in the high-frequency oscillating circuits used in radio.

In looking over the curves, I notice that Dr. Whitehead gives the curve for a certain type of Western Electric tube in Fig. 13, and uses the diagram shown in Fig. 14. If that is so, there is an error in the curve, an error due to the 1.5 meghoms, which is connected in the circuit. If in taking a curve we make the grid at all positive, of course the grid will draw current, and this current will have to flow through the 1.5 megohm resistance, and the drop in this resistance will be very high compared to the voltage being used. For example, if we have two micro-amperes flowing in the grid circuit, which is a pretty small current, if the two micro-amperes go through 1.5 megohms, there is a drop of 3 volts in the resistance. If we have 4 volts in the grid battery, the grid will be positive only to the extent of one volt. It looks to me as if something of that kind may have taken place, because it is very seldom in the Western Electric tubes of that type that the plate current falls away so rapidly, and becomes horizontal, as indicated in Fig. 13.

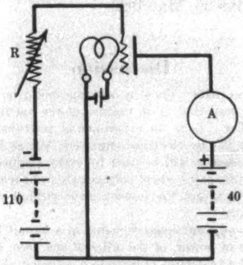


FIG. 2

G. D. Robinson: I would like to call to Dr. Whitehead's attention a circuit differing somewhat from the one that he has shown.

In the corona voltmeter we are interested in an extremely small flow of current through the more or less ionized gas between electrodes in the meter. When the gas between the electrodes is normal the resistance between them is substantially infinite, but at the moment that corona starts appreciable ionization occurs and this resistance drops to a lower, but still enormous, value. As the current which can be passed through this ionized gas is insufficient to give a deflection on a portable meter, it has become desirable to cause this small current to control a larger current which can operate the portable meter. Dr. Whitehead's circuit uses the *I R* drop caused by the flow of this small current through a resistance unit to control the grid voltage and plate current of a three-element vacuum tube. The variation of this circuit which I have in mind makes use of the *I R* drop *through the tube itself*, from filament to grid, to produce a similar result. The circuit will be as shown in Fig. 2. Here *R* represents the variable resistance of the ionized gas path between electrodes. *A* is a sensitive portable meter, perhaps one giving full scale deflection with one milliampere. I have found it desirable in a similar case to use more voltage in the grid circuit than in the plate circuit. The figures beside the batteries are possible values for these voltages.

In considering the effects of the grid upon currents in a circuit such as this it is customary to use curves showing the value of plate current and of grid current for various values of grid voltage. With negative grid voltages the grid current is so small that frequently it is neglected, but this current is *not* zero and in this case it is *not* negligible. When these characteristic curves have been taken with a sufficiently sensitive galvanometer it will be seen that any attempt to increase the negative grid current beyond a certain very small value will result in shutting off the plate current completely. This "very small value" will vary greatly with different tubes and different adjustments of plate and filament voltages. It is at least as small as 10^{-8} amperes in some tubes. Yesterday I obtained from Mr. Chubb of the W. E. & M. Co. the opinion that by removing the base, a three-element vacuum tube might be obtained in which a current of 10^{-12} amperes in the grid circuit would be enough to shut off the plate current. What does this mean? It means that if the ionized gas path in the corona voltmeter permits the passage of the *very small value* of current a change of current of the order of one milliampere can be obtained in the portable meter when corona starts.

This circuit does not satisfy the condition that the meter should read zero before corona starts, but obviously the meter could be shunted by a battery and resistance so that it would satisfy this condition. In the circuit shown in the figure the meter reading should be substantially constant at a large value before corona starts. At the start of corona the reading should *drop sharply*. I am of the opinion that this circuit can be made to give greater current amplification than was obtained by Dr. Whitehead.

As a-c. voltages applied to the grid of the vacuum tube will affect the reading of the d-c. meter in the plate circuit, precautions to reduce any such a-c. voltages to a small value would probably be required with this circuit.

John B. Whitehead: I wish to thank Professor Morecroft and Mr. Robinson for their suggestions in connection with the tube circuits. After a lapse of six months I can recall nothing which suggests that the connections in Fig. 14 were not used as there found. However, I understand that Professor Morecroft's comment refers particularly to the upper portion of the curve of Fig. 13, where the grid voltage becomes positive. The critical condition in which we are interested is that of zero value of the plate current when the grid has a considerable negative potential. It is quite possible, as Professor Morecroft suggests, that there may be some current in the grid circuit. If this is the case, the presence of the grid leak would undoubtedly cause the value of the grid voltage to be other than that indicated. The absence of the grid leak in Fig. 15 would therefore cause a change in condition. However, it will be noticed from Table 2 that observations were taken at various values of grid voltage, showing that the most effective were between 7.4 and 8.8.

As to Mr. Robinson's comment, I judge that he suggests that the indicating galvanometer shall carry current before corona forms, and fall to zero after corona forms, this result being accomplished by varying the current in the grid circuit. It is possible that a greater sensitivity may be obtained thereby, but I question whether the conditions will be as practicable and uniform as those well-known connections that we have used. Moreover, there is a considerable advantage in having the instrument stand permanently at zero, with deflection for the critical condition rather than the reverse. I hope that Mr. Robinson will have an opportunity to try the connection he suggests.

Prevention of Transient Voltage in Windings

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Review of the Subject.—*This paper relates to windings such as are used in transformers, reactors and the like, with particular reference to the characteristics which determine internal distributions of suddenly impressed voltages or sudden voltage changes, and the resulting internal oscillations. Ordinary lightning arresters, which limit the maximum voltages reaching the winding terminals, but cause rather than prevent the occurrence of sudden voltage changes, certainly give no protection against excessive voltages between turns or between coils. After describing the production of these transient voltages in ordinary windings, and pointing out that the treatment of symptoms by the addition of extra insulation tends to defeat itself by augmenting the cause, this paper explains these phenomena as due to faulty arrangements of inherent capacitance with the inductance of the winding. A fundamental principle is evolved indicating the constitutional remedy, which, if perfectly applied, would give only uniform internal voltage distributions, however abrupt or frequent the voltage changes at the terminals might be. Methods of application are described for the ordinary windings, by supplementing the faulty arrangements of inherent capacitance with auxiliary capacitances or condensers. Methods are given, also, for the construction of windings with the ideal distribution of inherent capacitance called for by the principle.*

Two alternative statements of the fundamental principle upon which the ideal distribution of capacitance is based are emphasized in the paper, and the application of the principle is adequately illustrated in the figures, of which Fig. 2 is a simplified diagrammatic representation of the arrangement of inherent capacitance with the inductance of that certain type of ordinary windings shown in Fig. 1, Figs. 3 to 5 illustrate methods of correcting this faulty arrangement by means of supplementary condensers, Figs. 6 and 7 show two typical forms of a general method of constructing windings with the ideal distribution of inherent capacitance, and the remaining figures illustrate practical modifications of this method.

With the ideal distribution of capacitance with inductance called for by the fundamental principle here enunciated, sudden and erratic changes in voltage at the terminals of the winding, or impressed wave trains of any frequency, result only in voltage distributions which are at every instant uniform. With practical arrangements approximating the ideal one, it is only necessary to insulate between turns and between coils, with ordinary factors of safety, for the proportional part of the maximum voltage which may appear at the terminals.

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HOW TRANSIENT VOLTAGES ARE SET UP IN ORDINARY WINDINGS

In ordinary electrical windings, in which all of the turns link a common magnetic circuit, such as those for alternating current transformers or reactances, any fluctuating or alternating voltage existing across or in the windings, unless the fluctuations or changes within the cycle are very rapid, has at each instant of time a practically uniform distribution throughout the winding. Voltages between points in the winding at any instance are approximately proportional to the numbers of intervening turns. Practically uniform voltage distribution thus prevails throughout such windings in normal steady operation at ordinary commercial frequencies. On the other hand, the resulting voltage distribution at the instant of a sudden voltage change, as from the closing of a switch, is far from uniform, and results in an internal oscillation. Moreover, voltage distributions and oscillations due to successive sudden voltage changes will superpose, augmenting each other if in synchronism and in phase, but tending to neutralize each other if in phase opposition. The internal voltages resulting in this manner from a succession of sudden voltage changes thus depend upon the way the changes are timed with respect to each other. Similar results will be produced, if the voltage changes at the terminals are sufficiently rapid, even though they are not absolutely instantaneous. With an external oscillation or high-frequency wave train arriving at the terminals, if the frequency is the same as the frequency of the internal oscillations, internal resonance will occur, and excessive voltages may be produced between neighboring portions of the winding. A single large sudden or quick change of voltage at the terminals of a winding may, in fact, produce transient voltages between turns which are very large as compared with those corresponding to uniform distribution, and the insulation stresses resulting from a succession of voltage impulses or a high-frequency wave train may become relatively much higher than those due to a single impulse.

Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

EXTRA INSULATION CONSTITUTES TREATMENT OF SYMPTOMS

Occurrences of the phenomena described above have demonstrated themselves in practise through years of painful experience, in the rupture of insulation between turns and between coils, resulting from switching, arcing grounds and lightning. As demands for reliability increased, and experience seemed to show the need of it, the insulation was increased, until its effect upon the cost and characteristics of transformers became a serious handicap. An unfortunate and for a long time mysterious phase of the situation lay in the fact that each increment in the insulation provided seemed to be followed, and as we can now understand, actually was followed, by a corresponding increment in the transient voltages which might appear to break it down. (From what follows, this will be seen to be due to the reduction of capacitance between turns caused by the increased thickness of the intervening spaces occupied by the insulation.)

OBJECT OF THE PAPER

While it has long been known that these results were due to capacitance within the winding, it is obviously impossible to eliminate capacitance, and the subject was not sufficiently well understood to avoid the evil effects. It is the object of this paper to enunciate a fundamental principle whereby the evil effects of capacitance in windings can be avoided, and to describe several practical methods for the application of this principle. The principle involved becomes obvious and will be stated after a brief review of the way capacitance occurs in windings and of how it affects voltage distribution.

DISTRIBUTION OF CAPACITANCE

Every portion of the inductance of any winding, as represented by a turn or a coil, may be considered as having a certain amount of capacitance in parallel with it, as the capacitance between turns and the capacitance between coils. The conclusions which it is here desired to draw from these considerations will not be affected by the fact that these capacitances are distributed around the turns and through the coils. Capacitances or elements of capacitance are also found between the various parts of the winding and grounded parts of the apparatus or surrounding objects, which will be included under the general term of capacitance to ground.

EFFECT OF CAPACITANCE ON INITIAL DISTRIBUTION OF SUDDENLY IMPRESSED VOLTAGES

Any voltage appearing suddenly at the terminals of such a combination of inductance and capacitance must be accompanied by an impulse of current necessary to charge the various elements of capacitance. The charge for each element is transmitted through other capacitance elements in series with it, since no current can flow through the inductance at the first instant. It is evident, therefore, that the voltage distribution at the first instant will be that due to the action of capacitance alone. In the ordinary winding, this distribution will be far from uniform with respect to the turns and coils of the winding, the instantaneous voltage across the end turns, for instance, being relatively very great.

EFFECT OF CAPACITANCE ON INITIAL DISTRIBUTION OF CURRENT GROWTH

The voltage across each individual turn, resulting from the initial distribution due to capacitance, constitutes the initial impressed voltage for that particular turn. This voltage must be opposed by an equal voltage magnetically induced in the turn: This induced voltage, however, is not merely that due to the self-inductance of the individual turn, but it is the summation of the voltage of self-inductance, which is due to the growth of current in this turn alone, and all the voltages of mutual inductance set up in this turn by the growths of current in other turns. The growth of current will be maximum in those turns for which the impressed voltage is maximum while in the turns of minimum impressed voltage the current growth may be minimum in the positive sense, or it may be in the negative sense with maximum negative value. A negative growth of current will occur in any turn in which the summation of voltage of mutual inductance due to current growths in other turns which is opposed to the impressed voltage for that turn is greater than this impressed voltage.

PRODUCTION OF INTERNAL OSCILLATIONS

The natural tendency of this initial distribution of current growth, by redistributing the condenser charges, is toward a uniform distribution of the voltage. Unfortunately, however, as this condition is approached we find a nonuniform distribution of current. With perfect mutual inductance between all of the turns, the current would become uniform at the proper instant, and both current and voltage distribution would remain uniform, but on account of magnetic leakage between different parts of the winding, the current can be brought to uniformity only after a further redistribution of voltage, giving maximum voltages where minimum voltages were previously found, and vice versa.

SUPERPOSITION OF OSCILLATIONS

We have thus roughly outlined the first swing of an internal oscillation which will be gradually damped out, resulting in a condition of uniform voltage distribution provided there are no further quick voltage changes at the terminals. If a succession of such voltage changes appear, the voltage distribution and oscillations which would be caused by each change will be superposed upon the remaining effects of all previous changes.

FUNDAMENTAL PRINCIPLE ON WHICH THE CONSTITUTIONAL REMEDY IS BASED

The fundamental principle whereby these non-uniform voltage distributions and oscillations may be eliminated from windings will now be stated as follows: *If the capacitance associated with any inductance is so disposed that the initial distribution of a suddenly impressed voltage, which is effected by the capacitance, is uniform with respect to the inductance, the growth of current within the inductance will be uniform, and the voltage distribution will therefore remain uniform, each element of capacitance receiving charge at the same rate that it loses it.*

In a winding which meets these conditions, the current in all parts will be the same at each instant of time. The action within a given turn of the mutual inductances between it and the various other turns, in this case, will be exactly like and simultaneous with that of its own self-inductance. These mutual inductances are with propriety, therefore, all included with the strictly self-inductance of the turn as the inductance referred to in the statement of the principle, although it is necessary to distinguish between the self-inductance of the turn and mutual inductances between it and other turns in considering the effects of quick voltage changes when this principle is not complied with.

PERFECT CURE WOULD RESULT FROM EXACT APPLICATION

In a winding fully complying with this principle, the voltage distribution would be uniform at all times, without regard to the abruptness or frequency of voltage changes at its terminals. The voltage which could appear across the insulation between turns or between coils would be limited to a value proportioned to the voltage at the winding terminals by the ratio of the number of intervening turns with the total number of turns in the winding. To provide the insulation necessary for safety, therefore, it would be necessary to consider only the proportional part of the maximum voltage which can appear, or would be permitted to appear, across the total winding. Moreover, for the provision of suitable external protection, it would be necessary to limit only the maximum voltage the suddenness and frequency with which voltage changes occur being of no importance.

APPROXIMATE METHODS GIVING PRACTICAL RESULTS

Several methods will now be described whereby a disposition of capacitance in accordance with this principle may be obtained with sufficient approximation for practical purposes, thus reducing the insulating of windings to a rational basis wherein the internal insulation required bears a definite relation to the normal operating voltage between the parts involved, as expressed by moderate factors of safety, and at the same time removing the necessity for restrictions as to switching, eliminating the danger from arcing grounds and simplifying the duties of lightning arresters.

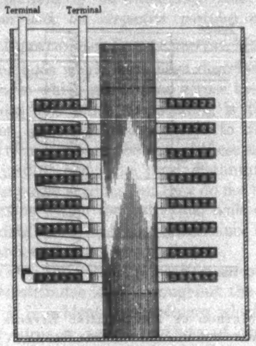

FIG. 1—REACTOR WINDING IN CROSS-SECTION—CASE AND LAMINATED CORE GROUNDED

The reactor is chosen for illustration instead of a transformer on account of its more simple arrangement of inherent capacitance, which is shown diagrammatically in Fig. 2. The methods of correcting faulty arrangements of capacitance, illustrated in Figs. 3, 4 and 5 with reference to this winding, if correctly carried out, are applicable to the more complicated cases of transformers.

GENERAL METHOD APPLICABLE TO ORDINARY WINDINGS, SUPPLEMENTING INHERENT CAPACITANCE

A general method suggests itself which is applicable to ordinary windings, by the provision of a system of supplementary capacitances or condensers, so proportioned and interconnected with the winding as to give the desired disposition of combined supplementary

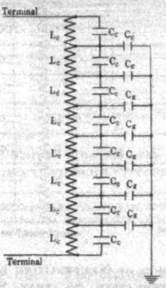

FIG. 2—ARRANGEMENT OF INHERENT CAPACITANCE WITH INDUCTANCE IN THE REACTOR OF FIG. 1, SOMEWHAT SIMPLIFIED

Inductance elements L_c correspond to the individual coils, condenser elements C_c represent capacitances between coils and condenser elements C_g represent capacitances to grounded core and case. Without ground capacitance, the initial distribution of suddenly impressed voltages would be uniform. The ground capacitances cause greater initial voltages across coils which are nearer to the line terminals, resulting in subsequent oscillations.

and inherent capacitance. This is illustrated in connection with the very simple arrangement shown in Fig. 2, which is here chosen for simplicity of treatment. This diagram represents a simplification of the disposition of inherent capacitance in the reactor winding of Fig. 1. The capacitances between coils appear as equal condenser elements, C_c, in parallel with the equal inductance elements, L_c, which represent the inductances of the individual coils. The condenser elements, C_g represent capacitances to ground or to neighboring conducting surfaces. If the ground capacitances could be eliminated, and if the arrangement of inherent capacitance with inductance were adequately represented by the C_c and L_c elements of Fig. 2, this would constitute an ideal arrangement in which the initial distribution of a suddenly impressed voltage would be uniform. The ground capacitances result in a condition for the various coils with respect to the suddenly impressed voltage, with which we are familiar in connection with suspension insulators, where the maximum voltage appears across the disk at the line end of the string. In the winding, the initial voltages will be greater for coils which are nearer to the line terminal, and these initial voltage distributions result in oscillations, as described above, due to reactions between the inductance elements and the capacitance elements. Specific methods for correcting this faulty disposition of inherent capacitance by means of supplementary condensers, which, if correctly carried out, are applicable to the more complicated cases of transformers, will now be given.

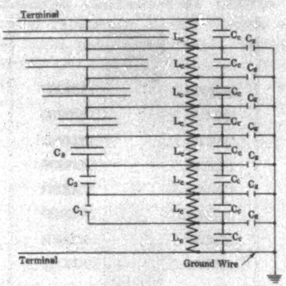

FIG. 3—A METHOD OF NEUTRALIZING EFFECTS OF GROUND CAPACITANCE IN ARRANGEMENT SHOWN IN FIG. 2

This method is applicable only when the winding is definitely grounded at some point. It consists in connecting condensers C_1, C_2, etc., across individual coils, the capacities of the respective condensers being given by the equation $C_n = \frac{n^2+n}{2} C_g$, where n is the number of the supplementary condenser, counting from the point of grounding.

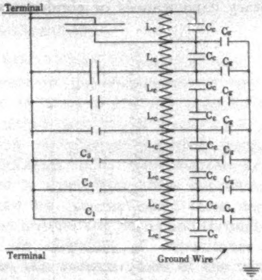

FIG. 4—A METHOD OF NEUTRALIZING EFFECTS OF GROUND CAPACITANCE ALTERNATIVE TO THAT SHOWN IN FIG. 3, APPLICABLE ONLY WHEN WINDING IS GROUNDED

Condensers C_1, C_2, etc., are connected between the line terminals and various points of connection between coils. The capacities of the respective condensers are given by the equation $C_n = \frac{n}{N-n} C_g$, where n is the number of the supplementary condenser, counting from the point of grounding, and N is the number of coils between this point and the line terminal.

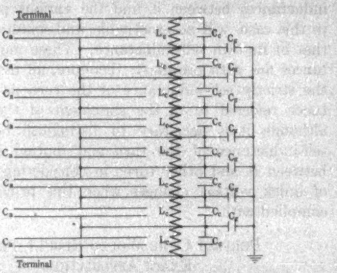

FIG. 5—A METHOD OF NEUTRALIZING EFFECTS OF GROUND CAPACITANCE IN ARRANGEMENT SHOWN IN FIG. 2, WHICH DOES NOT REQUIRE GROUNDING

The condensers, C_a, connected across the individual coils, must be large as compared with the inherent ground capacitances or possible inequalities between intercoil capacitances. If the coil inductances are unequal, these condensers must be unequal, their capacitances being in inverse proportion with the inductances.

METHODS LIMITED TO GROUNDED WINDING

If the winding is definitely grounded at one end, we will be able to neutralize the effects of the C_g elements, by means of supplementary condenser elements, by either if the methods illustrated in Figs. 3 and 4. With all the capacitance elements C_g equal, the required capacitance of any supplementary condenser C_n, in Fig. 3, is

$$C_n = \frac{n^2 + n}{2} C_g$$

and the required capacitance in Fig. 4 is

$$C_n = \frac{n}{N-n} C_g,$$

where n is the number of the condenser, counting from the grounded end, and N is the total number of coils.

METHOD WITHOUT GROUND LIMITATIONS

To carry out correctly the arrangements shown in Figs. 3 and 4 would require an indefinite number of sizes of auxiliary condenser units to fit the different cases and definite knowledge of the amounts and locations of the inherent capacitances of the winding. Moreover, they would possess the obvious disadvantage that they can be applied only in connection with a grounded winding. A method without these disadvantages is illustrated in Fig. 5, where the auxiliary condenser units, C_a, are all equal, and of sufficient size to overpower the inherent capacitances to ground. That is, the capacitance C_g is negligibly small in comparison with the capacitance of an auxiliary condenser unit. With this arrangement it makes no difference where the ground is located on the protected winding, or whether or not it is grounded at all.

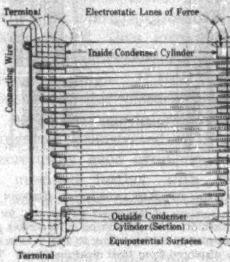
Terminal
Electrostatic Lines of Force
Inside Condenser Cylinder
Connecting Wire
Outside Condenser Cylinder (Section)
Equipotential Surfaces
Terminal

FIG. 6—TAPERED SINGLE-LAYER WINDING EMBEDDED IN DIELECTRIC OF A CONDENSER CONSISTING OF TWO CONCENTRIC CYLINDERS

The condensers plates (cylinders), are respectively connected to the winding terminals, and the winding progresses gradually, turn by turn, in the radial direction from one plate to the other, so that the electrostatic potential impressed upon each turn by the action of the condenser field corresponds to a uniform distribution of voltage. Nonuniform voltage distributions and internal oscillations cannot occur in windings so disposed.

MORE GENERAL CASE AND ALTERNATIVE STATEMENT OF FUNDAMENTAL PRINCIPLE

The method illustrated in Fig. 5 has been described in connection with a winding in which the various inductance portions were assumed to be equal. It is clear, however, that the same general method is applicable to any winding in which leads for connection to condenser units are brought out at convenient intervals, breaking up the inductance into parts which may not be equal. In this case, the capacitances of the auxiliary condenser units must not be equal but must be proportioned in accordance with the fundamental principle given above. For this application the principle may be stated in a more convenient form, as follows:

To give uniform distribution, with respect to the inductance, of voltages appearing suddenly across the terminals of windings, the capacitances in parallel with all of the various portions of the inductance must be in inverse proportion with the respective portions of inductance.

LIMITATIONS OF SUPPLEMENTAL METHODS

The methods which have been described insure that the voltages which can appear across the various coils or portions into which the winding is divided by the condenser leads are proportional to the respective portions of inductance, the sum of these partial voltages at any instant being the total instantaneous voltage across the whole winding, but they do not insure uniform distributions within the individual coils or portions of the winding, since the way capacitance occurs within these portions has not been affected.

If the way the voltage appearing across any individual coil distributes itself throughout the coil were not affected it is evident that voltages which may appear between turns or across portions of the coil will be reduced in the same proportion as that across the whole coil. As a matter of fact the reduction in voltage between turns or across portions of the coil will be greater in proportion than that across the coil as a whole, and this proportional reduction will be more marked the larger the auxiliary capacitances which are used. This is on account of the relatively large amount of electricity required to charge the auxiliary condensers, and the limited current which can be supplied from the line. The change in voltage across the entire winding, and consequently, that across the individual coil, will be less rapid with the condensers than without them, and less non-uniformity of voltage distribution among the turns of the coil result naturally from the more gradual change across the coil as a whole.

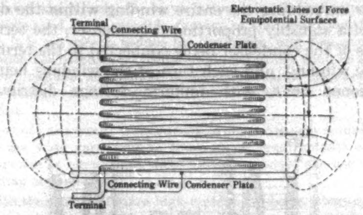

FIG. 7—CYLINDRICAL SINGLE-LAYER WINDING EMBEDDED IN DIELECTRIC OF A CONDENSER CONSISTING OF TWO PARALLEL PLATES

The equivalent arrangements shown here and in Fig. 6 are typical forms of a general method for the construction of windings with the ideal distribution of inherent capacitance.

METHOD OF CONSTRUCTING WINDINGS WITH IDEAL DISTRIBUTION OF INHERENT CAPACITANCE

The methods which have thus far been described are applicable as a corrective measure in connection with ordinary windings of previous types. It is, however, possible to design and build windings in which the inherent capacitances will have the ideal distribution, so that no supplementary condensers will be needed. A general method which completely meets the conditions for uniform voltage distribution with respect to the individual turns, without the use of supplementary condensers, is illustrated in typical forms in Figs. 6 and 7. This method consists in enclosing or embedding the entire winding within the dielectric of a suitably proportioned condenser, the terminal plates of the condenser being connected to the terminals of the winding, and each turn of the winding being so positioned that, with uniform voltage distribution, its potential will be the same as that which would exist in the part of the dielectric where the turn is located if the winding were not present. Turn by turn or element by element, the winding traverses the dielectric of the condenser, progressing gradually from one terminal plate toward the other. Modifications of these typical forms, embodying multilayer constructions, are shown in Figs. 8 and 11.

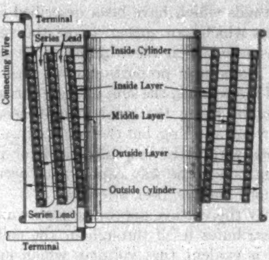
Terminal
Series Lead
Connecting Wire
Inside Cylinder
Inside Layer
Middle Layer
Outside Layer
Outside Cylinder
Series Lead
Terminal

FIG. 8—MULTILAYER WINDING, IN CROSS-SECTION OF TYPE SHOWN IN FIG. 6

The last turn of one layer is connected to the first turn of the next layer by a series lead passing between the layers. Except for the disturbing effect of these leads, which constitutes a departure from ideal conditions, this arrangement gives the same results as a single layer of three times the length, progressing gradually from one cylindrical plate to the other. A slight modification of this arrangement would result from making the winding layers cylindrical and tapering the plates.

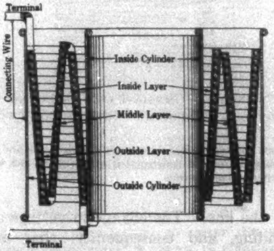
Terminal
Connecting Wire
Inside Cylinder
Inside Layer
Middle Layer
Outside Layer
Outside Cylinder
Terminal

FIG. 9—ARRANGEMENT EQUIVALENT TO THAT SHOWN IN FIG. 8

The series leads between layers are eliminated by inverting the middle layer.

EFFECT OF WINDING CONDUCTOR THICKNESS

A matter to be noted in connection with these arrangements of windings between condenser plates is found in the fact that the winding conductor occupies space which otherwise would be occupied by the dielectric of the condenser. If this conductor possessed only length and breadth, lying within equipotential surfaces, no effect would be felt, but due to its thickness in the direction of the field, it eliminates or short-circuits all potential drops within the space occupied. So far as the dielectric is concerned the effective distance between the plates is thus reduced by the combined thickness of the intervening conductors. In fixing the relative distances of the various turns from the respective plates, the thickness of intervening

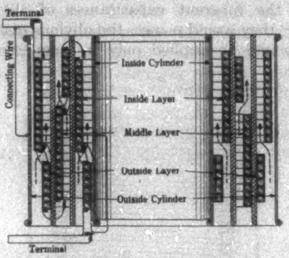
Terminal
Connecting Wire
Inside Cylinder
Inside Layer
Middle Layer
Outside Layer
Outside Cylinder
Terminal

FIG. 10—MODIFICATION OF ARRANGEMENT SHOWN IN FIG. 9

Cylindrical layers or sections of layers are substituted for the tapered layers. With the mid turn of each layer section in its correct position with respect to the condenser plates, corresponding to Fig. 9, it is seen that the other turns are slightly displaced from their ideal positions. This arrangement permits the introduction between layers of insulating cylinders and of passages for the circulation of cooling fluid. These passages are offset as indicated by the curved arrows.

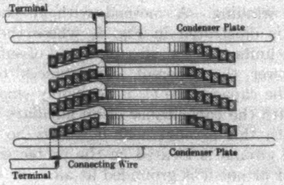
Terminal
Condenser Plate
Condenser Plate
Connecting Wire
Terminal

FIG. 11—MULTICOIL WINDING OF TYPE SIMILAR TO THAT SHOWN IN FIG. 7, THE COILS BEING CONICAL IN SHAPE INSTEAD OF CYLINDRICAL

The arrangement of this winding with respect to the disk-shaped condenser is similar to that of Fig. 8 with respect to the cylindrical condenser A slight modification of this arrangement would result from making the coils flat and the condenser plates concial. Other practical modifications of this arrangement, similar to those shown in Figs. 9 and 10 for the arrangement of Fig. 8, are obvious.

conductors should be neglected, measuring only those portions of distance which are within the dielectric, and, of course, measuring in each case to the adjacent surface of the turn, and not to the center of its section.

PRACTICAL MODIFICATIONS AND APPROXIMATE METHODS

As in the case of all engineering applications, practical considerations must here be taken into account. With the arrangement shown in Fig. 8, we find a disturbing element in the leads passing between the layers for connecting adjacent layers in series. These leads locally reduce the effective distance through the dielectric between layers, thus introducing extra voltage stresses. This becomes important when the normal layer voltages are high. If this were the only matter to be considered, this disturbing element might be escaped by inverting intermediate layers, giving the arrangement illustrated in Fig. 9. This would be a theoretically good arrangement, but one which may be modified further with several important practical advantages, making the arrangement only a little less good from the standpoint of voltage distribution. Thus, in the arrangement shown in Fig. 10, cylindrical insulating barriers have been introduced between adjacent layers, ducts have been opened up for the free circulation of cooling fluid, and the winding layers have become cylindrical instead of tapered. The middle point of each cylindrical layer portion of the winding occupies its ideal position in the dielectric, while turns on opposite sides of each mid-turn make slight departures from their ideal positions in opposite directions, the departure increasing gradually as we pass further from the mid-turn. This will permit corresponding departures from uniform initial distributions of suddenly impressed voltages within the individual layer sections, although the distribution of the total terminal voltage among the different sections will be in proportion with the numbers of turns between respective mid-turns.

Discussion

M. E. Skinner: I do not understand from the paper that actual transformers or even reactors have been constructed in which the inherent but rather disturbing effects of leads, connections and taps, space occupied by the conductors themselves, and of non-uniform inductance per turn, have been overcome. The paper appears to crystallize several ideas as to how these inherent difficulties may be overcome, but the structures illustrated are still a long way from anything employed at the present time in power or distribution transformer construction. It is interesting to note that the solution chosen for the problem of taps is their complete elimination. This is undoubtedly the most effective as well as the easiest way out. The fact that it has been found advisable to reinforce the insulation of the end turns of so simple a winding as that employed in an air core reactor, illustrates the difficulty of applying the principle upon which Mr. Weed's paper is based to commercial apparatus.

In this connection I should like to point out that the number of transformers which fail from overheating and from mechanical stresses is probably as great as the number which fail from voltage stresses. Of the insulation failures, relatively few occur between line turns. It would therefore appear as though the present practise of padding the insulation between the turns connected to the line was taking care of the situation admirably and this with no decrease in mechanical or thermal reliability and at very little increase in cost.

The picture drawn by Mr. Weed of the ease with which high voltages are built up in a transformer winding is rather alarming. However, it is comforting to remember that actual exhibitions of these high voltages on commercial systems are rare.

I believe that more improvement in service records will result from a reduction in the number of taps and leads, and from more thorough insulation of these exposed points in transformer windings than from such a delicately balanced winding construction as is proposed in this paper.

F. F. Brand: Mr. Weed is to be congratulated on the clear manner in which he has outlined the theory of transient voltages in windings and methods of eliminating them in simple cases.

There are unfortunately other factors than insulation to be considered in transformer design. Some of these fundamentally tend to have an opposite effect on the design.

Consider only the mechanical forces between windings. These are naturally higher in low-voltage transformers than in those for high voltages. The smaller insulating clearances necessary, the better space factor of the windings, result in increased flux densities surrounding the windings and thus result in higher forces.

For this reason the style of winding most suitable for low voltages may be radically different from that suitable for high voltages. In the former, mechanical force problems may predominate, in the latter, insulation problems.

Thus any method which makes it easier to insulate between the various parts of the structure, which enables the windings to be made more compact, increases the mechanical forces, and this must be considered in selecting the type of winding.

There is also a limit, due to variation in insulating value of the materials used, or to possible damage of the insulation, beyond which it is not safe to reduce the insulation and this, in connection with the mechanical forces produced under such conditions as short circuits, may make it uneconomical or impractical to use windings of the types illustrated which can be perfectly shielded.

Most of our present transmission systems are very complicated, there are wide variations in transformer requirements even on one system or circuit and these militate against the use of such shielding arrangement.

With the growth of extra high-voltage systems, where synchronous regulation becomes necessary, where systems assume the type of great trunk lines, the transformer requirement should become more fixed under all operating conditions. Furthermore the tendency to use solidly grounded neutral enables radical departure in transformer design to be made. These facts may and should allow the use of more perfect shielding of windings than has yet been accomplished commercially, although we must recognize that the grounded neutral system will probably increase the frequency of short circuits, because every insulator failure at once develops into a short circuit, and thus mechanical conditions may again be of increased importance even in extra high-voltage designs.

H. O. Stephens: In considering the design of transformers to withstand the transient voltages which always occur in operation the designing engineer has the choice of four methods.

1. He may disregard all means of eliminating or reducing these excess voltages and must recognize that they will be present between turns, between coils, between windings and between windings and ground. In this case it will be necessary to provide sufficient insulation at all of these points to withstand the maximum transient voltages that may occur under the most severe operating conditions.

2. He may use lightning arresters at all points of danger to prevent rises in voltage materially above the line voltage. He may use high-frequency absorbers to prevent line oscillations below the discharge voltage of the arresters. He may shunt inductances with resistors where possible in order further to absorb the energy in high-frequency oscillations. If the expedients employed to keep the abnormal transient voltages as low as possible are wholly successful, he may insulate the transformer between adjacent parts to withstand only the normal voltages with a reasonable factor of safety.

3. He may design the transformer along the lines brought out by Mr. Weed's paper so that the relation between inductances and capacitances within the transformer are such that a uniform distribution of transient voltages throughout the windings will be obtained. In this case he may also provide the transformer with only the necessary insulation to withstand the normal voltages with a reasonable factor of safety.

4. He may choose a proper balance between all of the three methods outlined above, using lightning arresters and whatever means are available for reducing the transient voltages to a minimum, designing the transformer so as to obtain as uniform a distribution of voltages throughout the windings as practicable and finally providing sufficient insulation to withstand the voltages which calculation and experience show will be developed between the adjacent parts of the windings.

Transformer design consists so largely in choosing a proper balance between diametrically opposing characteristics that it is seldom possible to carry out any single idea to its logical conclusion. If it were always possible to design transformers with the simple types of windings shown in Mr. Weed's paper it would be feasible to carry out the shielded winding construction to its full possibilities. Unfortunately however, the transformer is the connecting link in all systems between all other electrical apparatus and must therefore be adapted to all of the peculiarities and vagaries of all apparatus and systems. Even in the simplest design taps are usually necessary to compensate for variation in system conditions and a very large percentage of transformers have to be designed to operate on different parts of the same system and in some cases on different systems so that they may and very frequently do become extremely complicated. As soon as taps or series multiple connections are a necessary feature of the windings it becomes practically impossible to carry out a system of shielding the windings which will give anything like a uniform distribution of transient voltages.

In the present state of the art it would appear that the best engineering judgment would dictate that we follow the middle ground outlined under paragraph four. Experience has shown that with proper consideration given to system layout and operation, with careful disposition of the transformer windings so as to avoid groupings that will actually invite dangerous resonant conditions, and with reliable insulations so disposed as to insure ample protection against these now well-understood transient voltages, modern high-voltage transformers have proved very reliable from an insulation standpoint.

However, Mr. Weed deserves much credit for the way he has worked up this physical conception of the behavior of transients and even if it may never prove entirely practical to adopt it in its entirety, there is no doubt that consideration of this method of preventing dangerous rises in voltage has already been of considerable benefit to the transformer designer in teaching him how to avoid specially objectionable combinations of internal inductance and capacitance.

L. F. Blume: The value of Mr. Weed's paper consists in its emphasis of the fundamental principles which govern the relation between inductance and capacitance of a winding. A transformer winding, reactor or similar electrical apparatus, usually classed as possessing the property of concentrated inductance is in reality a very complex circuit consisting of a large number of inductances and capacitances in series and in parallel. For example, a typical transformer winding possesses capacitances from turn to turn, from layer to layer, from coil to coil and also from the external surfaces to other parts of the apparatus and to ground. These capacitances are so enmeshed with each other and with the various inductances of which the winding is composed that it is generally hopeless to disentangle them for purposes of analysis.

However by clearly describing an ideal principle of design Mr. Weed makes a forward step towards the understanding of the problem, and, what was heretofore a hopelessly complex mesh-work now becomes a regular pattern of inductances and capacitances the action of which is readily understood.

The principle may be crudely stated as follows:

Imagine that the conductors in a winding are broken at each turn so that no current can flow through the copper. Under this condition the voltage distribution within the windings due to an alternating source of potential is entirely governed by the capacitances possessed by the windings.

If the winding has been designed so that the voltage distribution throughout the winding under the aforementioned condition is identical with the voltage distribution under ordinary conditions, then there can never be an interchange of current between the inductance and capacitance portions of the winding and therefore under all conditions of excitation, normal and abnormal, the voltage distribution remains unchanged.

Several transformer windings built in Pittsfield in accordance with this principle were subjected to all sorts of high-frequency tests and voltage impulses. A complete verification of its theory was obtained. In attempting to apply this principle, however the designer cannot lose sight of other very practical considerations. Mechanical strength, cost of winding, reactance, cooling and insulation, all require due thought and at best a design is a compromise in order that all of these may be properly taken care of. The elimination of internal concentrations or their reduction to a minimum is one of these, and the designer has the choice of reducing the abnormal stress by skillful manipulation of the capacitances or of employing sufficient insulation to withstand them.

The various shielded windings which are described by Mr. Weed differ from ordinary windings used in transformers mainly in two respects. First, a metal shield is connected to each terminal. Second, capacitance of the winding to ground is eliminated.

From these differences it is a simple step to the conclusion that voltage concentration and internal resonance in ordinary windings is largely due to the small surface area of the winding terminals, and to the comparatively large capacitance of the coil surface to other parts and to ground; and by increasing the one and decreasing the other improvement in coil design from the standpoint of transient voltages might be expected.

Appreciable improvements can thus be secured in many transformer windings without employing the rather radical departures that are suggested by Mr. Weed, and without sacrificing other important considerations. For example the use of a metal clamping plate in close proximity to the end coils and electrically connected to the terminals in a cylindrical coil structure very effectively reduces the voltage concentration on the end turns when a surge occurs. Again by shortening the coil stack the surface capacitance to ground is decreased and by this means voltage concentration under abnormal conditions is appreciably lessened.

Whether it is desirable to proceed further toward the ideal winding depends in addition to the limitations imposed by other design considerations mentioned above, upon whether the abnormal voltages introduced are sufficiently severe or occur sufficiently often, and whether the use of more insulation may not serve just as well.

Abnormal voltage stresses due to any cause whatever occurs at most, only occasionally and then the duration is extremely brief. This, together with the fact that a given insulation is capable of withstanding for very short time a much greater stress than for longer periods, helps to reduce materially the burden on the insulation.

The above facts are presented not for the purpose of discounting in any way the value of Mr. Weed's paper, but to point out that failure of applying to practise entirely the principle in the manner described by him is due not to a lack of appreciation of the importance of the theory but to many other factors that help to determine the nature of the design

C. L. Fortescue: This paper is very interesting to me for many reasons. One of them is that I recognize the same ideas that have been used in connection with obtaining better distribution on strings of insulators. It seems rather peculiar that transformer windings and strings of insulators should require similar methods in order to get good distribution under transient conditions, but such is the case. If you could imagine a uniform inductance which has no distributed capacity, that inductance under an impulse would divide the impulse equally throughout all parts of its windings. However, it is impossible to get an inductance without distributed capacity, and therefore we must consider what determines the distribution of the impulse through a winding which has distributed capacity.

First of all, leave out of account the inductance itself. If we have capacity, in order to determine the potential of that capacity, we must have charge. That means we must have current flowing for a finite time. The impulse of voltage across the inductance is determined by the rate of change of the impulse, and therefore we cannot pass sufficient current in a given time to charge up the connected capacity to the right potential. In order to get the proper distribution, we must take the capacity part of our system, and so design it as to give uniform distribution of voltage.

In Fig. 3, of Mr. Weed's paper we have one method which is prosposed. That method is identical with that known in insulator strings as grading the insulators, that is to say, the insulator in the line which has a greater part of the capacity current, due to distributed capacity to take care of, is made of larger capacity—its capacity admittance is increased, and as the insulators approach towards ground, the capacity is graded,—those near the ground end being of less capacity than those near the line end. This method has been found quite effective, in giving proper distribution, and of course the distribution is entirely independent of the frequency or the rate of change.

Fig. 4 corresponds to the use of shields, such as the distribution shield at the terminal of the insulator string on the high-voltage side. This shield increases the capacity of the lower insulators, the line insulators, to the line, and grades the capacity in a manner similar to that shown by Mr. Weed; that is to say the capacity to the line is of such a magnitude that it completely annuls the distortion due to capacity to ground or the distributed capacity of the insulator string.

Fig. 5 shows another method that is being considered in connection with improving the distribution of potential over strings in insulators, that is to say, by making the capacity between adjacent insulators large compared with the capacity of the hardware to ground so that the latter becomes negligible as compared to the capacity between insulators. In this way a very excellent string distribution can be obtained.

Fig. 6 illustrates another method of shielding. For example, in the case of a string of insulators, if we put on the top and bottom of the insulators, a shield sufficiently large to give a field in the neighborhood of the string corresponding to that between two infinite parallel planes, we shall have a condition such that each insulator will have a capacity to the ground shield and a capacity to the high-potential shield of such value as to maintain each at its proper potential, and we shall get a string distribution, determined simply by the capacity between adjacent insulators.

Nine years ago I called attention of the Institute in a paper to a general theorem of electrostatics on systems of conductors having potentials, which covers in a general way the principles for obtaining any desired potential distribution. It may be stated in the following way: Arrange the system so that its natural potential distribution shall correspond to the natural electric distribution due to end electrodes or terminals. If you do this, you will get a condition in which there is no discharge between the individual members and the external space and you will then have the most efficient system.

As far as the application of these ideas to tranformers is concerned, I think certain types of winding tend towards the elimination of these transient maldistributions. The tendency is to use a distributed form of winding in which the high-tension part of the winding is removed from the ground as far as possible, and therefore its capacity to ground is decreased while of course, its capacity towards the high-tension terminals is correspondingly increased. The capacity is large for such a type of winding and it has a great deal of strength against transients coming in on the line. It approximates very closely the characteristics Mr. Weed pointed out.

J. F. Peters: When one considers the enormous voltages that theoretical considerations indicate have been produced in transformers which have been operating on comparatively high-voltage systems in the past, one wonders why any of them continue to live through the service; yet transformer failures have been comparatively rare. In more recent years the neutral of most high- and moderately high-voltage systems have been grounded either directly or through resistance, thus eliminating or greatly reducing the possibility of arcing grounds—the principal cause of high-voltage disturbances. In recent years the few insulation failures in transformers to my knowledge were not in or near the end coils and were all in ungrounded-neutral delta-connected banks.

That does not prove that comparatively high voltages may not appear across the end turns of transformers, but it does indicate that the present practise in insulation is adequate for the service, and it is accomplished with reasonable cost.

The paper presented by Mr. Weed is very interesting indeed. It shows theoretically how the maximum voltages in transformers can be reduced, but to actually approach even approximately the theoretical "constitutional remedy" outlined in the paper would be extremely difficult and very expensive. The schemes discussed by the author in connection with Figs. 8, 9 and 10 are, I believe, not as simple as one may be led to believe. With the arrangements shown in these figures it is assumed, I believe, that the total inductance of each turn is the same as that of every other turn throughout the winding. That, however, is not the case. The current that flows through the winding, due to an abruptly applied voltage, appears as a magnetizing current and a uniform current throughout the winding will not produce a uniform voltage.

This is because the magnetic circuit is not symmetrical with respect to all turns. This condition can best be seen by considering a number of identical coils located side by side and all connected in parallel. When an a-c. voltage is applied to these coils the outer or end coils will take very much greater current than the inner ones and the difference between currents of outer and inner coils will be greater the higher the applied frequency. That is, the more abrupt the applied voltage the greater will be the unequal division of current. Therefore, in order to get a uniform voltage across all turns of the structures, shown in Figs. 8, 9 and 10, the rate of change in current in the end turns of all layers must be much greater than that for the inner turns. In order to produce the proper current in all turns during the initial adjustment, the coils would have to be curved in cross section instead of straight, as indicated, which would be difficult to carry out in practise.

The schemes shown by Figs. 3, 4, and 5 and particularly that shown by 5, could be incorporated in any transformers, but it is very probable that after bringing out the additional leads and adding the cost of condensers, that the resulting transformer would be more expensive and less reliable than those built according to present practise, which are proving themselves entirely adequate.

F. W. Peek, Jr.: It was my good fortune to witness the tests and to take part to some extent in the work of which the shield described by Mr. Weed is one of the practical applications. In that investigation, made at Pittsfield, in about 1912, various types of transformers were taken and subjected to disturbances corresponding to those produced by arcing grounds. Taps were brought out from the different coils and the voltage distribution throughout the winding was measured by sphere gaps. Very high voltages may be produced in any part of the winding by varying the frequency of the disturbance.

It is surprising that a static shield can be effective in eliminating these very high local transient voltages. Yet that such is the case has been demonstrated by tests. The ideal shield described in the paper is difficult to apply in practise. However, it is approximated in practise in the way of clamping rings and considerable advantage is gained thereby.

It may be of interest to point out here that the operation of the shield is very similar to the stress distributing ring now used on high-voltage line insulators. There is this difference, however, in a transformer the voltage distribution under normal conditions is determined by the windings. The ring functions only under abnormal conditions. In the insulator the shield determines the normal distribution as well as the abnormal distribution.

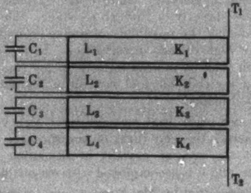

FIG. 1—FOUR COILS OF A TRANSFORMER CONNECTED IN SERIES

Letter C indicates the capacity of the coil, L the inductance of the coil and K denominates the coil T_1 and T_2 are the terminals.

P. Trombetta (communicated after adjournment): I find it very difficult to understand how the author got his conclusions, I find also that the paper contains some very specific contradictions which if taken seriously will upset either all his reasoning, his conclusions or both. Under the topic, "Object of the Paper," he states that it has long been known that the high voltage resulting at the terminal coils of transformer windings is due to the presence of capacitance and that it is obviously impossible to eliminate capacitance and that the subject was not sufficiently well understood to avoid the evil effects. On the other hand, farther on he proposes to eliminate these evil effects by introducing more capacitance. It seems quite clear to the writer that if the complete elimination of the capacitance would clear the effects certainly the nearer we get to the complete elimination the better should be the results and therefore it is impossible to see how by adding more capacitance we cure the effects.

A closer study of the phenomenon will, however, show that the burning of terminal coils in transformers is due to a phenomenon which is not at all mentioned in Mr. Weed's paper and which may be explained as follows:

In Fig. 1, K_1, K_2, K_3, K_4 represent four coils of a transformer; L_1, L_2, L_3, L_4 represent the inductance of the respective coils, C_1, C_2, C_3, C_4 represent the capacity between turns of the respective coils. Now as shown by Dr. Steinmetz, any system which contains distributed capacity and inductance has no fixed period of oscillation and any piece of such system may oscillate by itself irrespective of the rest of the system, so if we apply a voltage at the terminals T_1, T_2 of this transformer, we may have the transformer as a whole oscillating or any one of the coils may oscillate by itself or in combination with any number of the rest of them. Now it is well known that if an oscillating system is made up of a capacity connected in parallel with an inductance with very low resistance, at the resonance frequency we obtain the effect known as "Effet de Bouchon," which means that the circuit in which the oscillations are taking place is stopped up and no current can pass through it. The vector diagram for such a circuit is shown in Fig. 2 in which E is the applied e. m. f., I_c the current flowing in the condenser circuit, and I_L the current flowing in the inductance circuit. It is shown in this diagram that if the resistance is zero we may get enormous currents flowing through the condenser and the inductance while no current can flow through the main circuit. Therefore, if we say coil K_1 in Fig. 1 is set in oscillation at resonance and no current can flow through the circuit, the voltage drop through all the rest of the coils would be zero and the total voltage applied to K_1 is equal to the total voltage of the line. In other words, in this case of the four coil transformer, the voltage applied to K_1 would be four times its normal voltage and hence the insulation is broken down which results in the burning of the transformer.

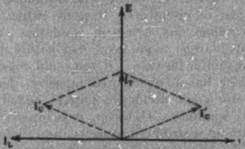

FIG. 2—VECTOR DIAGRAM OF A CIRCUIT CONTAINING CAPACITY AND INDUCTANCE IN PARALLEL

I_C and I_L represent the currents in the condenser and inductance respectively. I_T represents the vector sum of the two currents in phase with the e. m. f.; I_C and I_L represent the current vector of such a circuti when it is in resonance and neither the condenser nor the inductance have any resistance. I_C' and I_L' represent the same vector in case the condenser and inductance have resistances.

The conditions for the above effects are more favorable the smaller the capacity C_1 and the larger the inductance L_1 of the coil because in order to start the oscillation some current actually has to pass through all of the coils and the value of initial current depends upon the capacity C, that is, by increasing C the amount of current which must pass through the whole transformer before the system can be set in oscillation is increased on account of the fact that by increasing C the frequency of oscillations is decreased. On the other hand, it is impossible to pass within a very short time any appreciable current through the whole transformer due to its inductance and therefore by making C large enough we can prevent oscillations altogether.

J. Murray Weed: My chief effort in this paper was to give a clear conception of the causes of transient voltages and voltage oscillations in windings, with a theoretical solution of the problem of preventing them. I fully realized the difficulties involved in making general application of this solution, and the impossibility of making any application perfect, but I felt that it was not necessary to emphasize these phases of the subject. The danger is not that we will go too far in our efforts to make these applications, but rather that conservatism will unduly restrict our efforts in this direction. I feel that a thorough knowledge of the fundamental principles should enable us to make partial applications which will result in better transformers, or in transformers of equal value at less cost.

This is being done at the present time in the consideration given to the effects of various winding arrangements upon the distribution of capacitance, and in the use of metal clamping plates which are connected to the outgoing leads.

In the figures of the paper, I have suggested several methods of making approximations to the ideal arrangement, some of which may be found useful for practical application in suitable cases. I did not expect that any of the methods suggested would find general application, but I have gone as far as I have been able to go in pointing the way, and I would not be surprised to see the application of the general method here illustrated carried much further than seems to be expected by most of those who have discussed the paper.

Two or three points in the discussion require specific consideration.

In Mr. Blume's statement of the points wherein the shielded windings which I have described differ from ordinary windings, he has omitted one of prime importance. This point is brought out in the paper, but I take this occasion to emphasize it. To meet completely the conditions for uniform voltage distribution, each turn must be so positioned within the dielectric of the condenser that the potential which would be imparted to it by the electrostatic field, assuming that this field is not disturbed by the presence of the inductance is that which gives a uniform voltage distribution with respect to the inductance.

Mr. Peters has recognized a condition which no one can appreciate more keenly than I. It is practically impossible to perfectly meet the condition specified in the preceding paragraph, which constitutes the essence of the "Constitutional Remedy." The discrepancy due to variations in the inductances of different turns in a transformer winding, however, is not so serious as Mr. Peters seems to think. I presume that the results he speaks of were obtained with coils which were not linked with an iron core. That the inductances of all turns in a transformer winding are practically equal is demonstrated by the fact that transformer design is based upon this principle, primary and secondary voltages being proportional to the respective number of turns. There is, however, a tendency in the direction which Mr. Peters has spoken of, especially for high voltage windings, which are distant from the core. That I do not consider a moderate discrepancy of this sort serious is sufficiently indicated by my proposal, in the last paragraph of the paper, of the arrangement shown in Fig. 10. My conception of the effects of such discrepancies or failures to meet perfectly the conditions for uniform voltage distribution is given in the paper under the heading "Limitations of Supplemental Methods."

As for Mr. Trombetta, I feel that he may obtain a better understanding of the paper if he reads it again, together with the discussion which has been contributed by the others. His coil K_1, of course, is a part of the winding, and cannot act alone in the manner which he has described. Whatever its action, it comes within the scope of the theory which I have set forth.

Colloid Chemistry*

BY WILDER D. BANCROFT

Professor of Physical Chemistry, Cornell University

THE Chairman of your Program Committee wrote to me that he wished my talk to be a popular presentation which would interest the members who came to the meeting and also a profound discussion which could be read with profit by the eighteen thousand members who decided not to come. Either alternative is a large order and the two are mutually inconsistent, so I am not likely to satisfy anybody. Your Chairman evidently forgot that, if I were to tell you all the things which I consider interesting about the theory of colloid chemistry, I should keep going for several weeks. I give my unfortunate class at least twenty-five lectures at full speed on this very point. I am going to compromise tonight by telling you of a few things which might reasonably be of interest to electrical engineers, without making any attempt to cover the whole ground.

Speaking broadly, we can define colloid chemistry as the chemistry of bubbles, drops, grains, filaments, and films. These are things of which at least one dimension is small. In other words colloid chemistry is the chemistry of materials in which the surface is large relatively to the mass. For this reason one rather flippant person suggested calling the subject superficial chemistry; but some of us objected to the connotations.

Not so very long ago it was the fashion for the lecturer to present colloid chemistry as a succession of miracles. It was said to constitute a separate world of matter in which none of the facts of ordinary chemistry are so. Barium sulphate and metallic gold are soluble in water; metallic silver is blue, red, or yellow; globulin has a gram molecular weight of 700,000; a suspension of gamboge in water behaves like an ideal gas with a molecular weight of 200,000 tons; colloidal platinum is an inorganic ferment and is poisoned by potassium cyanide or by corrosive sublimate; all systems are in a state of flux undergoing irreversible changes.

Fortunately those days are over and we now try to make the phenomena of colloid chemistry seem the most obvious things in the world. If we start with adsorption and the Brownian movements, everything else follows fairly satisfactory; but these two concepts have not been familiar ones to the chemist and are perhaps quite unknown to the electrical engineer.

One property of every surface is that the surface tends to condense upon itself everything else with which it comes in contact in amounts which vary with the nature and structure of the surface, the nature of the substance in contact with the surface, the pressure, and the temperature. This formation of a surface film with a relatively high concentration is called adsorption. To most of us that seems a harmless name for an observed fact; but there are people who do not like it. A distinguished biological physicist from Cincinnati claims that the crime of the century is not the demonetization of silver, but the way in which colloid chemists sail under the black flag of adsorption. This metaphor seems to me a bit mixed but that is of no importance. It is possible also that I may have misrepresented my friend. It may be that the demonetization of silver was the political crime of the last century and that adsorption is the chemical crime of this century.

We know that adsorption takes place and that it is specific; but we do not know why hydrogen or carbon monoxide concentrate at, or are adsorbed by, a charcoal surface, for instance. One explanation is that the hydrogen or the carbon monoxide is attached to the surface of the charcoal either by regular chemical bonds or by contravalences, thus forming something analogous to a chemical compound. We cannot go any further than this because the carbon particles in the charcoal hold to each other more firmly than they do to the hydrogen, which would not be the case if methane, acetylene, ethylene, or ethane had been formed. For most purposes, however, it is quite sufficient to know that hydrogen concentrates at, or is adsorbed by, a charcoal surface without bothering our heads as to the mechanism of the adsorption.

While the phenomena due to adsorption constitute practically the whole thing in colloid chemistry, we cannot dispense with the Brownian movements, when we are dealing with fine particles suspended in a liquid. If we drop a very fine particle of sand in water, the sand will tend to sink because it is denser than the water. According to the kinetic theory, the water molecules are in violent motion and consequently will bombard the sand particle continuously. If the particle is large relatively to the molecule, the bombardment will have relatively little effect upon it; but if the particle is very small, it will be driven first one way and then another by the buffeting of the water molecules. This actually happens and, under the microscope, the finely-divided particles of any solid may be seen moving continuously in a zig-zag fashion. This phenomenon was first observed in 1828 by an English botanist named Brown and was named after him.

As would be expected from the theory, the Brownian movements are less marked the larger the particles. In fact, there is no perceptible motion when the particles exceed 4μ in diameter, while particles with diameters of about $10\ \mu\mu$ give apparent trajectories up to $20\ \mu$. The speed of platinum particles having a diameter of $10\text{-}50\ \mu\mu$ has been estimated by Svedberg at $200\text{-}400\ \mu\mu$ per second; but Perrin does not believe that these estimates are accurate. With increasing vis-

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Lecture presented at the A. I. E. E. Midwinter Convention, February 16, 1922.

cosity of the liquid the Brownian movements decrease, which is what one would expect on any hypothesis.

It is easy to see that the bombardment by the water molecules will give rise to irregular movements; but I should have supposed that the general effect would have been equivalent to a fairly uniform bombardment from all sides. This is not the case, however, and, for some mathematical reason which I have never understood, the statistical effect is a greater bombardment from the bottom than from the top when the suspended particle is denser than the liquid and the reverse when the particle is less dense. This is so judiciously arranged that the force of gravity is balanced and consequently this absolutely hit-or-miss bombardment results in a practically uniform distribution of the particles throughout the mass of the liquid.

This practically uniform distribution occurs only when the particles are very fine and consequently it follows that we shall get a colloidal solution whenever we have sufficiently fine particles and keep them fine. If several of the fine particles agglomerate or coalesce to form a large particle, the Brownian movements will be unable to keep this larger particle suspended and it will sink to the bottom or rise to the top as the case may be.

There are two different ways in which we can keep fine particles from coalescing or agglomerating. One is to coat them with a suitable material film. You are perfectly familiar with this on a somewhat larger scale and under other conditions. You know that you can buy a pasteboard box containing several separate doses of a liquid medicine, castor oil for instance. The separate masses of liquid do not run together because each one is enclosed in a gelatine capsule. We can do the same thing with suspended particles. We can coat them with a film of gelatin or some other substance which will keep them from coalescing. In some extreme cases a film of adsorbed water or other liquid will prevent agglomeration. Water seems to do this for tannin. When pyroxylin is carried into apparent solution by acetone, the separate particles are kept from coalescing by a film of adsorbed acetone.

We can also keep suspended particles from coalescing by charging them electrically all with the same sign, in which case they tend to repel each other. If we have suspended particles which adsorb hydrogen ions very strongly and chlorine ions very slightly, we can stabilize that colloidal solution by adding hydrochloric acid, in which case the particles will all be charged positively by the adsorbed hydrogen ions. If the particles adsorb hydroxyl ions very strongly and sodium ions only slightly, we can stabilize such a colloidal solution by adding alkali. If we add caustic soda to hydrous chromic oxide, the latter goes into apparent solution and we get an apparently clear, green solution of what used to be called sodium chromite. Nowadays we know that it is a colloidal solution of chromic oxide, the oxide particles being charged negatively by adsorbed hydroxyl ions. Of course a colloidal solution which is stabilized by the adsorption of an ion, will be precipitated if we add an electrolyte which has a readily adsorbable ion of the opposite sign from that which stabilizes the solution. You are probably quite familiar with Acheson aquadag which stays up admirably in water but flocculates when salt is added.

Precipitation occurs on a large scale when muddy rivers flow into the sea. When rain falls in a clay country, the run-off is muddy. The Mississippi river is very muddy at St. Louis; but there is a good deal of relatively coarse clay in it, most of which settles out gradually. At New Orleans the river normally has much less clay than at St. Louis; but the clay particles are very fine and show very little tendency to settle. They are charged negatively by adsorbed hydroxyl ions and that checks coalescence. When the river flows into the Gulf of Mexico, the concentration of sodium ions is so great in the salt water that it more than makes up for the relatively slight degree of adsorption of the sodium ions and the adsorption of these latter neutralizes the negative charge on the clay which therefore precipitates, forming a delta. Of course, there is some settling, due to the current becoming zero; but the chief factor in the formation of deltas is the precipitation of the suspended clay by the salts in the sea water.

At one time we used to distinguish between colloidal solutions stabilized primarily by adsorbed ions and those which were not, calling the first suspension colloids and the second emulsion colloids, the particles in the first being solid and precipitated readily by electrolytes, while the particles in the second were liquid and were relatively insensitive to electrolytes. A classification of this sort is valuable in the early days; but it emphasizes differences which are not real and consequently such terms as suspension and emulsion colloids are now practically obsolete. We can make oil suspensions which are quite as sensitive to electrolytes as colloidal gold. Colloidal sulphur, though charged negatively, withstands high concentration of hydrochloric acid. Gelatin solutions are not affected much by most salts; but recent work shows that the hydrogen ion concentration is important. In other words, we get all gradations and there is nothing to be gained by making arbitrary distinctions.

Gelatin is interesting because certain special things coagulate it and make it insoluble. Tannin is one and chromic salts are another. If we add tannin or a chromic salt to gelatin, we make it insoluble. This is utilized technically in making leather. Vegetable tanning consists in adding tannin to the hide substance, which is very similar to gelatin and becomes insoluble. In chrome tanning we make the hide substance insoluble by the addition of chromic salts. This phenomenon is also made use of in certain photographic processes. Bichromate has no effect on gelatin; but if a bichromated gelatin is exposed to light, there is a reduction to a chromic salt and the gelatin therefore becomes insoluble where the light has struck it.

Having explained what we mean by colloidal solutions, I will take up a few cases of adsorption which may be of interest to you. A striking illustration is the gas mask in which the chief adsorbing agent is charcoal, which is very specific in its action, adsorbing certain substances much more strongly than others. If charcoal had adsorbed air in preference to poison gases it would have been useless as a protection against these latter. It was necessary that the charcoal should adsorb the toxic substances preferentially, that it should adsorb them very completely, and that it should adsorb them very rapidly. The requirements were very severe. The air may take only one-tenth of a second to pass through the canister and yet it may be necessary in that space of time to reduce the concentration of the toxic gas from, say, 1000 parts per million to 1 part per million or less. The charcoal developed by the Chemical Warfare Service met that requirement with a safe margin. In fact, in laboratory experiments, it was shown that the charcoal will reduce the very high concentration of 7000 parts per million of chloropicrin, CCl_3NO_2, in a rapidly moving current of air to less than 0.5 parts per million in something under 0.3 seconds. This was, of course, a special charcoal. On the first of July, 1917, the best charcoal that we had would not stop chloropicrin for one minute under the conditions of the standard test. The charcoal, made on a small scale later, stood up at least 1200 minutes against chloropicrin under the same condition. This gives an idea of what was done in the way of improvement, though the large-scale manufacture of charcoal did not give so effective a product.

The early use of charcoal as an adsorbent was quite a different one and runs back to the end of the eighteenth century. Solutions of raw sugars are dark colored but can be decolorized by treatment with charcoal. The charcoal takes out nearly all the coloring matter and only a little of the sugar and we therefore have a very effective purification. Here too the chemist has developed much better charcoals than were used originally. It is worth noting, however, that the charcoals which are best in the gas mask are not the best for decolorizing sugar. The two sets of service conditions are quite different. Although contact catalysis involves adsorption, it does not follow that the charcoal, which is the best catalytic agent for making phosgene, $COCl_2$, from carbon monoxide and chlorine, is either the best charcoal for the gas mask or the best charcoal for decolorizing sugar.

When decolorizing sugar, we are not interested in the fact that, theoretically, the coloring matter, which is removed from the sugar solution, changes the color of the charcoal. We have other cases of adsorption in which the important thing is the fixing of the coloring matter on the adsorbing agent. If we dip a piece of cloth in a suitable colored solution, and perhaps heat the solution to boiling, the cloth will take some or all of the coloring matter out of the solution and will be dyed. We distinguish a number of different types of dyes such as basic, acid, substantive, mordant, vat, and sulphur dyes. Some of these are in true solution and some are in colloidal solution; but in all these cases we are dealing with an adsorption of the dye or of a reduction product of the dye either by the fiber itself or by the mordanted fiber, and the mordanting of a fiber is also a case of adsorption.

When discussing charcoal, a reference was made to the catalytic manufacture of phosgene. It has long been known that porous materials accelerate certain reactions and that this effect is specific. This acceleration of reaction velocity by an undissolved substance which undergoes no marked change itself, is known as contact catalysis and is of the greatest value in technical processes. The so-called contact sulphuric acid is made by passing a mixture of carefully purified sulphur dioxide and air over finely divided platinum at about 450 deg. In the synthesis of ammonia from hydrogen and the nitrogen of the air, porous iron is the chief catalyst, though other substances, known as promoters, are added to increase the action of the iron. The oxidation of ammonia to nitric acid is done in the presence of platinum as catalytic agent, while nickel is used chiefly in the hydrogenation of oils. In making ethylene from alcohol as a preliminary stage in the manufacture of mustard gas, either alumina or kaolin is used as the catalytic agent. As yet, we do not know how the catalytic agent activates the reacting substance and we cannot predict at all what substances will make the best catalyzers in any given case. If we ever get a satisfactory theory of the subject, I think that catalytic methods of making all sorts of chemical compounds will drive out pretty nearly all the regular processes. The plants act in that way now, their catalytic agents being called enzymes.

If we have electrified particles, as we do in some of our colloidal solutions, they will move under the influence of a direct current. As electrical engineers you are familiar with the particular case of electrified solid or liquid particles in air, which is known as the Cottrell process for precipitating smokes. A high-voltage, direct current passes from a point to a plate, ionizing the air and charging the suspended particles, which are carried to the plate and can there be scraped off. I have seen the statement that, in the Washoe reduction works of the Anaconda Copper Company, the Cottrell process has been introduced on so large a scale that the point electrodes consist of one hundred and eleven miles of chains. The Cottrell process removes suspended solids or liquids; but, of course, will not remove a gas, such as sulphur dioxide for instance.

In the case of a colloidal solution, the charged particles will move with the current if they are charged positively, through having adsorbed a cation, and they will move against the current if they are charged negatively, owing to adsorption of an anion or to having emitted a cation. This transference under electrical stress consists in a motion of the particles relatively to the water. If we should in any way hold the particles stationary and leave the water free to move, we should expect an electrical stress to cause the water to flow past the particles, the water going to the anode if the particles are charged positively and to the cathode if the particles are charged negatively. This can be realized if we consolidate the particles into a porous diaphragm. Suppose we have a porous cup in a beaker with one electrode, the cathode, inside the cup and the other electrode, the anode, outside the cup. If the diaphragm is charged negatively, the liquid will flow through into the porous cup, eventually causing it to overflow. When the liquid passes through a diaphragm, the phenomenon is called electrical endosmose; when the suspended particles are carried through the liquid, the phenomenon is called cataphoresis. The word hylophoresis, or transport of matter, has been suggested as the general term covering both cases; but it has not yet been adopted.

Cataphoresis is the thing that has made electrolytic lead refining commercially feasible. Glue, or some similar material, is added to the bath and is carried to the cathode, where it modifies the structure of the lead so that it comes down as a fine-grained deposit and not as feathery crystals. The use of so-called addition agents is quite common in electro-plating and many of these are colloidal. The commercial applications of electrical endosmose have not been very successful as yet. By placing peat between two electrodes and passing a high-voltage current, the peat acts as a diaphragm and the water is squeezed out electrically. The water content of the peat can be reduced from ninety to sixty-five per cent with a reasonable expenditure of power; but the cost of getting the water content down to twenty per cent has proved excessive. The method is said to have been used successfully in drying alizarine paste and things of that sort, where the value of the product justified a greater expenditure for drying.

In addition to the adsorption of a gas or a liquid by a solid, we may also have the adsorption of a solid by solid. Several cases of this sort are of great interest to the electrical engineer. Theoretically, aluminum should be an utterly useless metal because it stands in the electrochemical series near the alkali metals and calcium, quite close to magnesium. We should expect it to corrode rapidly under almost any conditions; but that is not what happens. The reason that you can use aluminum for transmission lines, when the price of copper soars, is simply and solely because aluminum as a metal is a successful failure. Its natural duty in life is to corrode; but the oxide or hydroxide film which is formed is adsorbed so strongly by the metal that it protects the surface and thus stops further corrosion. The only reason why an aluminum wire or sauce-pan does not corrode is because the air and liquids do not come in contact with the metal. If we amalgamate aluminum, the oxide coating does not adhere and the metal corrodes rapidly, giving us the so-called fibrous alumina.

Nickel also becomes covered ordinarily with a strongly adsorbed film of oxide or hydroxide and consequently does not rust. In the case of iron the oxide film is usually not coherent and consequently the metal goes on rusting. It is possible, however, under special conditions, to give iron a coating of the magnetic oxide which protects the metal surprisingly well.

We speak of noble metals as ones that do not corrode in the air; but it is an open question in my mind how many metals can qualify under this definition. We know that platinum black is always oxidized in contact with air, which makes it probable that sheet platinum has an oxide film on it. Under ordinary conditions most of our metals do rust or corrode; but a good many of them, fortunately for us, stop corroding because of the formation of a protecting film. Zinc corrodes superficially and we all know that a copper roof turns green and then undergoes very little further change. As I see it, the corrosion problem is to treat a metal so that it will corrode to a limited extent and then stop. In other words we must study the conditions which cause the formation of a protecting film. Calorized iron is one solution of the problem, phosphatized iron is another solution, and there are doubtless many more.

A protecting film is not always a desirable thing. The difficulty in condensing zinc from zinc vapor is due to the fact that any zinc oxide which is formed is adsorbed strongly by the globules of liquid zinc as they form and we get blue powder instead of cast zinc. It is very difficult to melt aluminum scrap because of the oxide film around each piece. You are familiar with the fact that when dirty mercury is shaken, it forms globules which do not coalesce because of films of oxide or grease around each drop.

This brings us naturally to the question of emulsions, which are drops of one liquid suspended in another liquid. Since the two liquids in the ordinary emulsions are usually water and some form of oil, it has become customary to use the word oil for the non-aqueous liquid even though, as in the case of benzene, it is not strictly an oil. While we can make emulsions which are stabilized by an adsorbed ion, most actual emulsions are stabilized by the use of an emulsifying agent which forms a film around the drops of the suspended liquid. To emulsify oil in water, we are apt to use a sodium soap in the laboratory, while the pharmacist uses gum acacia a great deal. We can emulsify water in oil by using calcium soaps as in the case of some lubricating greases or we can use rosin in the case of paints in linseed oil. Whether we get water emulsified in oil or oil emulsified in water depends on the nature of the emulsifying agent and not on the relative masses of oil and water. Speaking broadly, an emulsifying agent, which goes more readily into water than into oil, will emulsify oil in water. The converse is also true. Emulsions are very important physiologically because Clowes has shown that protoplasm behaves in many respects like oil and water emulsified by a mixture of calcium and sodium soaps, the lipoid material being considered as oil.

If we replace the oil in an emulsion by air or a gas, we have a foam. You have probably seen advertisements of Foamite as a means of putting out fire. This consists of solutions of aluminum sulphate and sodium bicarbonate to which has been added some organic material such as licorice. When the two solutions are mixed, the chemical reactions may be written,

$$Al_2(SO_4)_3 + 3NaHCO_3 = Al_2O_3 + 3Na_2SO_4 + 6CO_2 + 3H_2O.$$

The alumina and licorice form a film round the bubbles of carbon dioxide giving a very stable foam.

A more important application of foam is the ore flotation process. If we shake up water to which a little oil has been added, we get a bubble of air surrounded by an oil film. This bubble is fragile and breaks on reaching the surface. If we have present a sulphide ore with a siliceous gangue, the siliceous gangue is wetted preferentially by water and the sulphide particles by the oil. The patent of the Minerals Separation Company calls for the use of a fraction of one per cent of oil per ton of ore. An ore pulp usually runs about one ton of ore to four or five tons of water. When air is beaten into this mass, the particles of the sulphide ore go into the oil-water interface or into the oil itself, stabilizing the film because we then have practically armor-plated bubbles. The resulting froth can be scraped or shovelled off. Since most of the sulphide ore rises with the froth and since most of the siliceous gangue stays in the water, a very effective separation occurs. In most cases acidification of the solution and rise of temperature increase the effectiveness of the separation.

If the amount of air is insufficient, the oil may cause the ore particles to agglomerate and sink. This was patented by Cattermole; but it is not technically so successful as the frothing process. If the amount of air is excessive relatively to the ore, the number of bubbles will be so great that the ore particles cannot coat them sufficiently to armor-plate them and a fragile froth will be formed. This principle is made use of in the Callow process, in which air is introduced in fine bubbles at the bottom of the cell. These bubbles break as soon as they reach the surface and consequently the ore particles must be removed before they settle back. We can thus have clotted particles, armor-plated bubbles, or fragile bubbles, according to the conditions.

Coming back for a moment to emulsions, there is a wonderful chance for somebody to discuss whether the most important natural emulsion is milk or the rubber latex. Milk is necessary to life in the early stages; but pneumatic tires play a very important part later in life. Milk is an emulsion of liquefied butter fat in water which contains some other things. As obtained from the cow, milk is not very satisfactory when considered solely as an emulsion, because a more concentrated emulsion known as cream rises fairly quickly. If milk is passed through a homogenizer, the fat globules are broken up into smaller, more nearly uniform drops and we get an emulsion which remains unchanged when passed through an ordinary separator. If the cow had been more efficient mechanically, it is probable that skimmed milk would never have been discovered. When the milk emulsion is broken up by churning, the liquefied butter fat hardens into butter. The rubber latex is the milky juice from various kinds of rubber plants, chiefly trees and vines. It is an emulsion of liquid rubber in water which contains other things. The rubber emulsion can be broken down in a great many ways. On the plantations it is usually done by adding acetic acid. The liquefied rubber hardens just as did the liquefied butter fat and the product is raw rubber. One reason that we do not let milk sour in order to get butter is that the caseine comes down too. I do not know whether acid breaks the butter emulsion and whether one can get butter by adding vinegar to cream.

Raw rubber is not a satisfactory product in itself because it is too brittle when cold and too sticky when warm. It has to be vulcanized, which usually means heating with sulphur. Vulcanization is a problem of adsorption. There is only one compound of sulphur with rubber. It contains thirty-two per cent of sulphur, has the formula $C_{10}H_{16}S_2$, and is known as hard rubber or ebonite. Ordinary vulcanized rubber contains perhaps four per cent of combined sulphur and must therefore consist chiefly of raw rubber with hard rubber adsorbed on the surface of the raw rubber. Most rubber chemists dispute this conclusion because it is not possible to dissolve raw rubber out of vulcanized rubber with the solvents which will carry pure raw rubber into colloidal solution. This is not a serious objection however because we have already seen that a film of aluminum oxide keeps aluminum from being acted on by things which corrode pure aluminum.

Electrical engineers are interested of course in insulation problems. In addition to rubber we have three other well-known substances which are valuable, each in its own way: porcelain, artificial silk, and bakelite. The manufacture of all these involves colloid chemistry; but a discussion of these substances would take me far beyond any reasonable time limit. I hope, however, that I have succeeded in showing you that colloid chemistry is a subject which is of real interest to the electrical engineer.

Heating of Railway Motors in Service and on Test-Floor Runs

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***Review of the Subject.**—The rating given to a motor is the manufacturer's guarantee of the motor performance under the conditions given on the name plate.*

Assuming that this rating is entirely safe, then the successful functioning of the motor depends entirely upon the application engineer's analysis of the particular duty that the motor will be required to perform.

Where the required motor output is practically constant the application is simple; however, in many cases the motor load is apt to be anything but constant, consisting of loads of all degrees of magnitude, and in such cases the economically correct application is especially difficult. The past improvements made in the motor design, mechanically and electrically, have resulted in greater importance of the motor-operating temperatures, in fact in the great majority of cases the motor rating is limited only by the motor temperature. It is obvious then that correct motor applications depend to a very great extent upon correct operating temperatures.

Ratings such as the continuous, short-time, normal, and duty-cycle ratings give the performance of the motors under some particular conditions; however, the duty required of a great number of industrial and railway motors will not agree with any of the above ratings. Thus the application of motors to cranes, hoists, steel mills, and railways must be made with the knowledge of the motor's performance under one or more arbitrary conditions.

In general the two ratings which should be known for motor application to such irregular duty are the continuous and a short-time rating. The time period of the short-time rating should not exceed one hour and in many cases a one-half hour run is preferable.

The correct application of a motor requires a knowledge of the thermal conditions inside of the motor. Thus it is evident that the motor must be able to dissipate eventually all of the heat losses generated. On a continuous load the final rate at which the heat is transferred from the motor to the air will be equal to the rate of heat generation.

The resulting temperature rise can be estimated with the physical conditions known. This is simply a problem in physics and involves the conditions of ventilation with the corresponding ventilating surfaces. To predetermine the internal temperatures requires a knowledge of the rate of heat flow along the various heat flow paths to the ventilating surfaces.

Under irregular loads the temperatures are transient and are determined not only by the conditions of ventilation and rates of heat flow, but also by the motor's ability to store heat, which is proportional to the product of the motor's mass and specific heat. Hence the temperature rise of any part of a motor under any given load for some definite time is a function of the rate of heat flow from that part to the surrounding air and its thermal capacity. Thus from the known physical conditions the temperature rise of the motor can be predetermined and with certain assumptions a simple equation can be developed which will give an approximate value of the motor temperature under any given load conditions.

When the constants of the theoretical equations are based upon tests (such as given by short-time and continuous rating) the above method of temperature predetermination will be sufficiently accurate for most practical purposes, and will make possible the calculation of the motor temperature rise under any duty cycle.

The temperatures referred to are not only those temperatures obtained by thermometers upon the surfaces of the machines, but also the maximum internal temperatures, since it is the latter temperatures which first produce insulation failure.

The temperatures obtained by thermometers bear no fixed relation to the maximum temperatures for all types of machines under various loads.

In order to have something concrete to work upon the writer has taken up the heating and cooling characteristics of railway motors. A brief analysis of the heating at the standard ratings is given. The fundamental equations defining the temperature rise of a motor on a continuous or short-time load are developed, and finally the applications of these equations are made in several specific examples.

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THE adoption of standard motor ratings for various types of service has greatly facilitated the correct application of the motors. However, the motor's performance can be relied upon only in those applications where the duty required of the motor is equivalent to that specified by the motor's rating. This introduces a factor of uncertainty in the application of the motor to such irregular and intermittent service as is required of crane, hoist, steel mill, and railway motors.

The selection of a proper motor for a particular railway service is without doubt one of the most difficult problems in motor application. For instance the street car motor is subject to daily rush hour loads; to possible heavy peak loads due to a steep track grade; and in addition to this it is called upon to deliver abnormal overloads resulting from conditions such as holiday crowds, trailer operation, snow or the necessity of pulling in a disabled car, and these conditions are apt to be accompanied by a low line voltage.

Railway motor failures may be classed as mechanical and electrical. A large part of the electrical failures is due either to poor commutation and flashing or to excessive temperatures. In the modern commutating-pole motor mechanical failures and those electrical ones which are caused by poor commutation have been greatly reduced; however, the possibility of breakdown due to high operating temperatures is still present. The modern high-speed, ventilated, commutating-pole motor will deliver a much greater output per pound of motor than the early types of railway

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motors. This means of course that the motor's capacity for the storage of heat on short-time overloads has been reduced and has resulted in making the peak load temperatures the predominating factor in some railway motor applications.

The purpose of this paper is primarily to discuss the heating of railway motors on the standard test floor runs and to develop a general method by which the heating can be predetermined for any given service. However, the analysis of the heating problem as given is general, and is applicable to the temperature predetermination of any rotating electric machine.

Standard Motor Ratings

The adoption of a simple test or combination of tests which would be a criterion of a motor's performance in any railway service has been recognized as impractical. With such intermittent loads the best general method of rating should be based upon the motor's overload or thermal capacity and upon its continuous rating. Thus the Standards of the American Institute of Electrical Engineers say that the nominal rating of a railway motor is that output which the motor will develop for one hour with a temperature rise by thermometer at the end of the run of not over 90 deg. cent. on the commutator, and 75 deg. cent. at any other normally accessible part. With this short-time run a majority of the heat losses is stored up in the motor so that this rating is to a certain degree a measure of the thermal capacity of the machine as a unit.

The continuous rating is defined as the input in amperes at which it may be operated continuously at ½, ¾ and full voltage respectively without exceeding a temperature rise of 65 deg. cent. by thermometer (85 deg. cent. by resistance) for Class A[1] insulation and 80 deg. cent. by thermometer (105 deg. cent. by resistance) for Class B[2] insulation.

Thus the continuous rating is a measure of the motor's ability to dissipate heat.

Distribution and Disposal of Heat Losses

With regard to ventilation there are three general classes of railway motors, namely, totally enclosed, self-ventilated and separately ventilated motors. The Institute Standards define a "totally enclosed" motor as one so enclosed as to prevent circulation of air between the inside and the outside of the case, but not sufficiently to be termed "air-tight." A "self-ventilated" machine is one in which the ventilating air is circulated through the machine by a fan, blower or centrifugal device integral with the machine. A "separately ventilated" machine has its ventilating air supplied by an independent fan or blower external to the machine.

Nominal One-Hour Rating

Table I gives the distribution of losses on four typical types of motors at the one-hour and the continuous rating. This nominal rating is purely an arbitrary one. As previously mentioned the rating is intended to be a standard of measurement of a motor's thermal capacity. The requirement for this is that no heat loss shall be dissipated from the motor, that is all of the losses must be stored in the motor masses. This condition is approximated in totally enclosed machines where the heat losses from the external frame by radiation and convection rarely exceed 10 per cent of the total loss.

TABLE I.

DISTRIBUTION AND DISPOSAL OF LOSSES IN RAILWAY MOTORS

Type of Ventilation	Enclosed		Self Ventilated				Separate Vent*	
Rating—Time	1 hr.	Cont	1 hr.	Cont	1 hr.	Cont	1 hr.	Cont
Volts	600	450	600	450	600	450	600	450
H. P.	60	..	65	..	25	..	200	..
Amperes	88	36	95	60	37	35	280	220
Rev. per min.	700	827	700	638	1225	950	670	550
Weight of bare motor	2350	..	2350	..	870	..	5200	..
Weight armature	615	..	615	..	225	..	1700	..
Armature watts loss:								
Armature copper	1800	301	2100	840	820	733	3980	2450
Armature iron and stray power	1170	560	1170	620	780	500	3250	2500
One-half friction and windage	300	400	325	280	220	155	900	700
Brush loss	264	108	285	180	111	105	840	660
Total armature loss	3534	1369	3880	1920	1931	1493	8970	5810
Field copper loss	1825	306	2360	950	650	580	4690	2900
One-half friction and windage	300	400	325	280	220	155	900	700
Total motor loss	5659	2075	6565	3150	2801	2228	14560	8910
Per cent copper loss	64.0	29.2	67.9	56.8	52.5	59.0	59.5	60.0
Armature loss per cent of total	62.3	66.0	59.1	61.0	69.0	67.0	61.6	59.5
Watts loss/lb. of motor	2.41	0.88	2.79	1.34	3.22	2.56	2.80	1.71
Armature loss/lb. of armature	5.75	2.22	6.31	3.12	8.68	6.65	5.28	3.13
Armature copper loss/lb. copper	26.5	4.4	30.9	12.3	36.4	32.6	14.7	9.1
Field copper loss/lb. copper	7.1	1.9	9.1	3.7	9.1	8.1	8.7	5.4
Disposal of losses:								
Per cent absorbed	81.4	0	81.9	0	57.5	0	69.0	0
Per cent dissipated from frame	10.8	100	4.6	62.0	12.5	45.0	4.9	14.3
Per cent carried away by the ventilation air through motor	7.8	0	13.5	38.0	30.0	55.0	26.1	85.7

*Separate ventilation on the continuous rating only.

In the early non-commutating-pole motors it was necessary to observe carefully commutation during this one-hour run and this necessitated the removal of the commutator cover. This practise is still used in the modern motors. In fact Rule No. 5202 of the Standards of the A. I. E. E. says that the covers should be arranged to secure maximum ventilation without external blower.

Some of the self-ventilated motors will circulate as much as 50 per cent more air with all covers off than with covers on as in service. This has resulted, as shown later, in the nominal rating being dependent upon ventilation as well as the thermal capacity of the motor. The table shows that of the total losses, from 59.1 to 69.0 per cent is found in the armature. Since the armature weight is only about one-third of the total motor, its thermal capacity (ability to store heat) on short-time loads will be less than that of the motor as a unit. It results in an armature loss per pound of armature of 5.28 to 8.58 watts. The armature copper loss per pound of copper ranges from 14.7 to 36.4 watts. A loss of 4.5 watts per pound of armature will raise its temperature 75 deg. cent. in one hour if all the loss is stored in the iron and copper. Hence in the 25-h. p. high-speed motor at least (8.58 − 4.5)/8.58 or 48 per cent of the total armature loss must be transferred elsewhere; with the larger motors this percentage is considerably reduced. A loss of 3.75 watts per pound of copper if all stored in the metal will raise its temperature 75 deg. cent. in one hour. This means that toward the end of the one-hour run with this motor by far the greater part of the heat loss generated in the armature copper must be transferred to the iron or air and but little of that loss is stored.

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[1] Class A insulation is composed of specially treated cotton, silk, paper or similar materials.

[2] Class B insulation is composed of material capable of resisting high temperatures such as mica and asbestos.

On the one-hour run the motor losses are stored up in the iron and copper, carried away by the ventilating air through the motor and dissipated from the external frame by radiation and convection. Table I shows that of the total loss about 81 per cent is stored in the motor parts for the first two motors while for the last two more highly ventilated motors this percentage is 57.5 and 69. This shows that the one-hour rating is not a true indication of the motor's thermal capacity, since the percentage of the heat loss stored in the motor during this run is a function of the motor's ventilation.

CONTINUOUS RATING

On continuous duty all of the heat losses in the motor must be transferred to the surrounding air, that is, this rating is not affected by the heat storage capacity of the motor. In a totally enclosed motor the total losses are transferred to the frame and are then liberated by radiation and convection. The frame temperature rise is approximately proportional to the watts per square inch to be liberated. The heat dissipated from the frame is about 0.013 watt per square inch of surface per deg. cent. rise. This is an average value from many tests. The surface is taken as that of a solid cylinder whose over-all dimensions are equal to those of the motor. The actual effective surface is greater than this due to the roughness of the castings and the numerous irregular projections. This accounts for the high value of this constant since the heat loss from a smooth surface due to natural convection and radiation is only about one-half of the above value. With a car speed of 10 mi. per hr. the above constant is approximately doubled. The internal temperature drop from the armature to the frame is a function of the ventilating surface and the internal ventilation. It is evident that the external ventilation on the frame can not affect this internal drop. The external frame rise on continuous duty averages about 60 per cent of the internal temperature rise when measured on the test floor by thermometers. The rating on an enclosed motor is limited by this low heat flow from the frame and by the temperature gradient necessary to cause the armature loss to be transmitted to the internal air and then from this air to the inner frame surface. For continuous-rated enclosed motors the weight per h. p. increases with the motor size. This may be seen for example by the fact that by doubling the motor's dimensions the external ventilating surface is increased to four times its first value while the weight is increased to eight times the original weight.

VENTILATED MOTORS

When air is circulated through a motor by either an internal or external fan the effect is two-fold. It reduces the internal air temperature and for a given loss it decreases the temperature gradient between the ventilating surface and the internal air. It is possible to reduce this temperature drop to a very small value with separate ventilation; however, the internal insulation drop is still present. This temperature difference between the copper and the ventilating surface is the limitation to the degree of ventilation economically possible. Thus Table I shows that the small 25-h. p. self-ventilated motor on the continuous run can dissipate 2.56 watts per pound of motor while the heavy locomotive motor (insulated for 1500 volts) with separate ventilation can get rid of only 1.71 watts on the basis of the same copper temperature rise. This is due to the large internal temperature drop in the windings and insulation of the larger motor which is independent of ventilation. The first two motors listed in the table give a comparison of continuous rating possible on a totally enclosed and a self-ventilated motor of the same weight. It shows that for the same internal temperature rise the enclosed motor can dissipate a loss of 2075 watts while the self-ventilated motor can dissipate 3150 watts. This difference will increase with the speed of the armature.

APPLICATION OF MOTOR

The usual method of applying a railway motor to any given service is to estimate the average root-mean-square current from the conditions known. The motor must have a continuous rating at least equal to this r. m. s. current. With this rating known the average operating temperature rise can be estimated from the above current. Due to the irregularity of the load it is necessary to see if the motor has sufficient overload or thermal capacity to take the peak loads without excessive temperature rise. This predetermination of temperature rise on intermittent duty is a very difficult problem, for which a rigid mathematical solution is practically impossible. However, a comparatively simple approximate solution is possible.

SOLUTION OF PROBLEM[3]

The following solution of this problem has been made on the assumption that the heat losses and ventilation in the motor or any part thereof considered are uniformly distributed. This is not strictly correct; practically however it is permissible since the heat losses will to a certain degree distribute themselves by conduction through the iron and copper.

(5) Total energy loss = stored energy + dissipated energy.

The solution of this equation is given in the appendix. The final equations are:

$$t = 2.3\, t_1 \log_{10} \frac{T_c - T_s}{T_c - T_t} \qquad (10)$$

or an equivalent form:

$$T_t = T_c - (T_c - T_s)\, e^{-t/t_1} \qquad (11)$$

where (e) is the Naperian base (2.718)

t = Time in hours the load is applied.

T_s = Temperature rise at start, deg. cent.

T_t = Temperature rise at end of time (t).

[4]T_c = Final temperature rise on continuous duty, and

$$T_c = \frac{W}{S_e\, r\, K_e + \dfrac{V\, S_i\, K_i}{V + 0.9\, S_i\, K_i}} \qquad (8)$$

W = Watts loss of motor or part considered.

S_e = External surface of motor frame in sq. in. This may be figured by considering the motor as a solid cylinder.

K_e = Heat dissipation from the external surface in watts/sq. in/deg. cent = 0.013 approximately when frame is stationary.

r = Ratio of external frame rise to the internal surface rise. This ratio is a function of the degree of ventilation of the motor. On enclosed motors it averages about 0.60; on self-ventilated motors 0.40; and with separately ventilated motors 0.20 to 0.30.

V = Volume of air passing through the motor in cu. ft./min.

S_i = Internal ventilating surfaces of the motor which come in contact with the ventilating air, sq. in.

K_i = Heat transfer from the ventilating surface to the air in watts/sq. in. of surface/deg. cent. difference between the surface and adjacent air. This is determined by the air velocity, direction of air flow with respect to the surface, and the nature of the surface. Fig. 1 shows the curve of an average value for this constant which was obtained from many tests made upon actual machines and experimental apparatus.

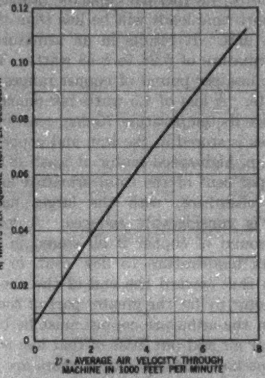

FIG. 1—SURFACE HEAT DISSIPATION

In watts per sq. in. of surface per deg. cent. difference between surface and air temperature.

It is incorrect to use the above equation (8) for self-ventilated motors where the air volumes V are relatively small. Under these conditions the heat transfer constant K_i is determined more by the peripheral speed of the armature than by the actual air velocity through the motor. Where separate ventilation is used the heat dissipation is practically independent of the armature speed; in this case the above equation is applicable.

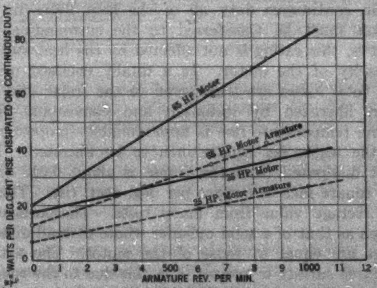

FIG. 2—HEAT LOSS

In watts per deg. cent. rise dissipated at various speeds at the continuous ratings for the motor and motor armature.

For self-ventilated motors the value of the continuous temperature rise T_c should be based upon test results.

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[3] The method of solving this problem was first suggested to the writer by Mr. C. E. Wilson.

[4] These temperatures are the average surface temperatures as obtained on the iron core.

This value is usually known for two or more speeds, that is the rating at 300 and 450 volts. If the watts loss per degrees centigrade rise (W/T_c) is plotted against the armature rev. per min. the points fall approximately on a straight line as shown in Fig. 2. The value of this constant for zero speed is approximately equal to 0.006 times the external surface of the motor. When the armature only is considered the value of W/T_c becomes approximately equal to 0.003 times the external motor surface for standstill conditions. Hence with one other test point the line is determined.

In equation (**9**)

$$t_1 = 0.06 \frac{(P_a + r\,P_i)}{W} T_c$$

t_1 = The thermal time constant of the motor and is the time in hours necessary to raise the temperature of the motor T_c deg. cent. with the loss W and no ventilation, that is with all of the energy absorbed in the motor.

P_a = Weight in pounds of the motor parts which have losses generated in them.

P_i = Weight in pounds of the motor parts which have no losses generated in them, such as the frame and end housings.

This constant t_1 can also be determined from tests. It is necessary to have a continuous and a short-time temperature test. Substitution in equations (**10**) or (**11**) will give the value of t_1.

Part I of the Appendix is a general solution and can be applied to the motor as a unit or to any part thereof. It may be advisable in some cases to consider the armature alone and in other cases to consider the fields. The temperature rises referred to here are the surface temperatures as measured by thermometers.

Part II gives the method to be used in order to obtain the actual internal copper temperature of the fields or armature windings.

METHOD OF APPLICATION

An example will probably clarify the above method for determining the temperature rise of a motor. For instance, calculate the heating curve of a particular 75 h. p. low-speed motor, separately ventilated with 800 cu. ft. of air per minute; the load to be 90 amperes at 600 volts. First find the final surface temperature rise T_c with the loss W, equation (**8**):

$$T_c = \frac{W}{S_e\,r\,K_e + \dfrac{V\,S_i\,K_i}{V + .9\,S_i\,K_i}}$$

Where:

W = 6610 watts (total motor loss)

S_e = 4740 sq. in. (external frame surface)

r = 0.30 (ratio of frame rise to the internal surface rise)

K_e = 0.013 heat dissipation from frame in watts/sq. in./ deg. cent.

V = 800 cu. ft./min. (air volume)

S_i = 5460 sq. in. (internal ventilating surface)

v = 2070 ft./min. (average air velocity through motor ducts)

K_i = 0.038 (heat dissipation constant, see Fig. 1).

Substituting these constants in the above equation the final rise T_c = 35.5 deg. cent.

The thermal time constant (see Equation **9**) is

$$t_1 = \frac{0.06\,(P_a + r\,P_i)\,T_c}{W}$$

where the weight of active material (P_a) = 1780 lb. and the weight of inactive material (P_i) = 1850 lb. With r, T_c and W as given above t_1 = 0.774. Hence with the initial temperature rise (T_s) known the rise at the end of any time (t) can be found from equation (**10**), where

$$t = 2.3\,t_1 \log_{10} \frac{T_c - T_s}{T_c - T_t}.$$

These values are plotted in Fig. 3. The results found in actual tests are also given.

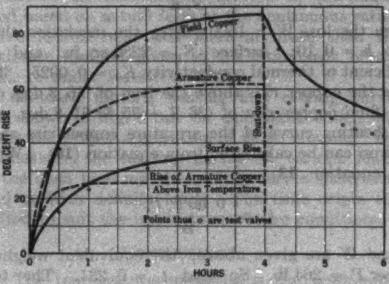


FIG. 3—HEATING CURVE OF 75-H. P. 600-VOLT D-C. RAILWAY MOTOR

Forced ventilation.
Load, 90 amperes, 600 volts.
Curves as calculated.

The temperature rise of the armature and field copper can also be found by using the method as given in Part II. The final rise of the commutating-pole copper (see equation **12**) is the surface rise, calculated above, plus the insulation drop. Thus

$$T_t = 35.5 + \frac{W\,h}{S_t\,K_t}$$

where the loss W = 1010 watts; insulation thickness (h) = 0.15 in.; the cross-section of the insulation for heat flow S_t = 1180 sq. in. and the thermal conductivity coefficient K_t = 0.0025. Hence the continuous field copper rise T_c = (35.5 + 51.5) = 87 deg. cent.

The surface temperature rise of the coil as given in Fig. 3 is seen to rise abruptly after shut-down when the ventilation is reduced. It is due to the decreased heat flow from the surface which results in a decrease in the temperature difference between the copper and the surface, in other words, the surface temperature must rise. The maximum point reached after shut-down will be somewhere between the copper temperature and the running surface temperature. The exact value of this will depend upon the thickness of insulation, the relative thermal capacity of the copper and the insulation; and the ratio of the ventilation when running and at shut-down. It is thus seen that this temperature rise of the surface at shut-down is a transient phenomenon and the temperature found by thermometer bears no fixed relation to the actual copper temperature for all conditions.

The final rise of the armature copper T_c above the iron (see equation **12**)

$$= \frac{W\,h}{S_t\,K_t}$$

where the loss $W = 1500$ watts; the insulation thickness $h = 0.10$; surface $S_t = 2280$ sq. in. and the coefficient of thermal conductivity $K_t = 0.0025$. This gives the copper rise above the iron of 26.3 deg. cent or a final copper rise of (26.3 + 35.5) 61.8 deg. cent. The heating curve of the armature copper rise above the iron can be calculated from equation (**10**). Where (see equation **13**)

$$t_1 = \frac{0.05\,P\,T_c}{W}\,.$$

T_c and W are given above; the equivalent weight of copper $P = 264$ lb. So that $t_1 = 0.231$. The temperature rise of the armature copper above the iron is shown in Fig. 3 plotted in dotted lines. The addition of this to the average surface rise of the motor will give the heating curve of the armature copper.

The air rise

$$T_a = 1.8\,\frac{(W - S_s\,r\,K_s\,T_s)}{V}$$

W being the total motor loss; the factor $(S_s\,r\,K_s\,T_s)$ being the loss dissipated from the frame. Substitution of these constants in the equation gives an air rise of 13.4 deg. cent. Test value was 13 deg. cent.

The following example will show how the temperature rise of a self-ventilated street car motor is calculated for a given cycle run. Given a 25-h. p. 600-volt, 37-ampere, d-c. motor to operate on the following cycle:

(1) A r. m. s. current of 27 amperes for three hours, schedule speed of 10 mi. per hr. with 26-in. diameter wheels and a gear ratio of 13/74.

2) 32 amperes for one hour; schedule speed of 8 mi. per hr.

(3) 27 amperes for two hours, schedule speed of 10 mi. per hr.

(4) 50 amperes for 30 minutes with a schedule speed of 6 mi. per hr.

What will the operating temperatures of the armature iron and copper be under the above cycle?

In this case only the armature is considered. The loss is composed of the copper, iron and stray power, brush and one-half of the friction and windage loss. The following tabulation gives the value of the constants and final equation for obtaining the heating curves of the armature iron or core:

Portion of Cycle	1	2	3	4
Amperes	27	32	27	50
Rev. per min.	735	588	735	441
Total armature loss (W)	937	1056	937	2105
Watts/deg. cent. of iron (see Fig. 2) W/T_c	21.6	18.7	21.6	15.6
Continuous core rise (T_c)	43.3	56.5	43.3	135.4
Weight of armature (P)	200 lb.	..	..	..
Thermal time constant: $t_1 = 0.06\,P\,T_c/W$	0.556	0.642	0.556	0.770

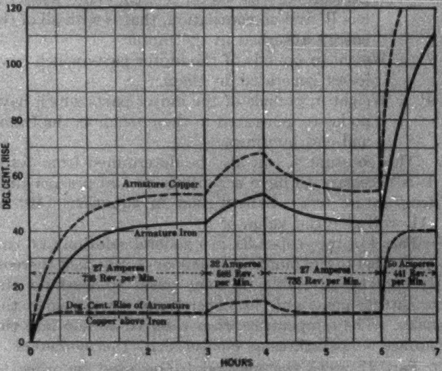


FIG. 4—HEATING CURVE OF ARMATURE IRON AND COPPER
25-h. p. 600-volt d-c. railway motor.

With the above constants the heating curve can be plotted from equation (**10**) where

$$t = 2.3\,t_1 \log_{10} \frac{T_c - T_s}{T_c - T_t}\,.$$

This curve is shown in Fig. 4 in solid lines.

The following tabulation will give the constants for obtaining the hot-spot correction, that is the maximum internal copper temperature rise above that measured by thermometers on the iron core.

Portion of cycle	1	2	3	4
Amperes	27	32	27	50
Imbedded cop. loss (W)	241	338	241	900

Constant copper rise above iron (see equation **12**):

$$T_c = \frac{W\,h}{S_t\,K_t} = 10.8\,\text{deg.cent.}\ 15.1\ 10.8\ 40.8$$

Equivalent copper weight (P) = 45 lb.

Thermal time constant:

$$t_1 = \frac{0.05\, P\, T_s}{W} \text{ (see equation 13)} = 0.101$$

With the above constants the heating curve giving the copper temperature rise above the iron can be found by using equation (10) where

$$t = 2.3\, t_1 \log_{10} \frac{T_e - T_s}{T_e - T_t}.$$

This curve is shown in dotted lines (Fig. 4). The addition of this curve to the heating curve obtained for the rise of the armature core will give the heating curve for the armature copper.

Both Figs. 3 and 4 illustrate the fact that the armature copper on the average ventilated motor has comparatively little thermal capacity. It is seen that on loads of thirty minutes or more practically all of the copper loss is being transferred through the insulation. The thermometer measurements will not give this internal temperature, hence it is possible to find a safe temperature rise on a motor by thermometer with a certain load although the motor may be dangerously hot in the inaccessible parts.

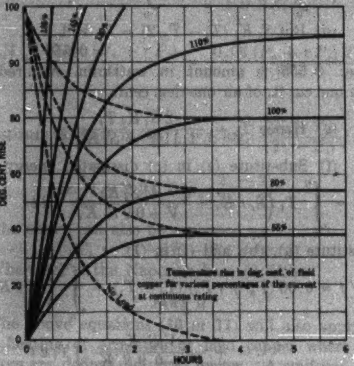


Fig. 5—Heating and Cooling Curves
75-h. p. 600-volt d-c. railway motor.
Separately ventilated.

There is no doubt but that from the standpoint of weight and cost the modern ventilated railway motor has an inherent advantage over the totally enclosed motor. It has been shown that since the ventilated motor can get rid of more heat losses than the same motor enclosed it is possible to rate the motor higher. This increases the continuous rating without materially increasing the one-hour or overload rating. The effect of ventilation is to decrease the surface temperature and to increase the gradient between the copper and the surface temperature. When a ventilated motor is applied to an intermittent cycle such as found in railway service, full advantage of the continuous rating cannot be taken since a margin in temperature is necessary in order to carry the heavy peak loads.

With the heavy enclosed motors the ratio of the hour to the continuous rating is high so that the application of such a motor on the basis of the average r. m. s. current is generally safe. The inherent thermal capacity of the motor will usually take care of the peak loads.

On the other hand the tendency of increasing the ventilation is to bring the continuous and the hour rating together. Hence the economical application of the modern high-speed ventilated motors must be made with more care, and the motors' performance from a thermal standpoint on such applications should be known.

The method of predetermining the temperatures of such motors on intermittent service as previously outlined based on actual tests at the continuous rating will give results safer and more accurate than the approximate method given in the Standards of the A. I. E. E. under Rule No. 5502.

For standard motors, heating and cooling curves such as shown in Fig. 5 can be calculated which will facilitate the proper application of these motors. The solid lines are the heating curves at various loads, while the dash lines are the cooling curves either with no-load or with definite loads. The time origin can be shifted to suit the initial temperature conditions.

CONCLUSIONS

(1) The temperature limitation is the predominating factor in railway motor application. This limitation is found in the maximum "hot-spot" temperature at the peak loads.

(2) The armature copper has relatively little thermal capacity which may result in high internal temperature gradients on short-time loads.

(3) The ratio of the one-hour to the continuous rating approaches unity as the ventilation of the motor is increased.

(4) The application of the ventilated motor on the basis of the average r. m. s. current to an intermittent duty is incorrect if the maximum internal temperature at the peak load is ignored.

(5) It is the maximum internal temperature which first starts insulation failure. Hence motor ratings should be based upon this temperature and not upon the surface temperature as measured by thermometer.

(6) There is no fixed relation connecting the internal maximum and the surface temperature as found by thermometers. This relation is affected by insulation thickness, degree of ventilation, duration and magnitude of load, together with size and accessibility of the motor windings.

(7) Thermocouple measurements provide the best means for obtaining these maximum temperatures. These temperatures can be approximated from the

maximum hot resistance of the windings. However, the obtaining of these hot resistances requires very quick and accurate work. Either of the above methods requires special apparatus and the services of expert observers in service tests.

It is obvious that the temperatures of a motor in service as obtained by thermometers may be so far from the maximum internal temperatures as to give misleading results.

Thermal characteristics of the motor, such as relation of thermometer to the thermocouple temperatures, must be known for all degrees of load in order to estimate the internal temperatures from the thermometer readings.

(8) The nominal rating as defined by the Standards of the A. I. E. E. and as applied to self-ventilated railway motors is a fictitious rating since it specifies the run to be made under abnormal conditions of ventilation due to the removal of ventilating and commutator covers and due to the fact that the motor speed is usually higher than the average speed found in service. This has resulted in its being no longer a true measure of the motor's thermal capacity. It is merely a measure of the motor's overload capacity under the conditions given.

It would be more logical to make this test under conditions of ventilation as used in service.

The writer, however, believes that the original purpose of the one-hour run, that is a measurement of the motor's thermal capacity, is essential and should be approximated as closely as possible. This can be done either by reducing the time of the run or by reducing the effect of the ventilation.

Appendix

PART I

TEMPERATURE RISE OF ELECTRIC MACHINES ON CONTINUOUS AND SHORT-TIME DUTY

Symbols.

Let W = Total watts loss in motor or part considered.

T_c = Final average surface rise deg. cent. on continuous duty.

T_t = Surface rise at end of time (t).

t = Time in hours the load is applied.

T_s = Average surface rise at start of cycle.

T_a = Temperature rise of ventilating air deg. cent.

V = Cubic feet of air per minute through the machine.

A = Cross-sectional area for air flow in sq. ft.

v = V/A = average air velocity through machine in ft./min.

S_e = External surface of machine in sq. in.

S_i = Internal ventilating surface of machine in sq. in.

K_i = Heat flow from internal ventilating surface in watts/sq. in./deg. cent. See Fig. 1.

K_e = Heat dissipated from external surface in watts/sq. in./deg. cent. Approximately 0.013 when stationary.

r = Approximate ratio of external frame rise to the internal surface rise.

P_a = Weight in pounds of active material.

P_i = Weight in pounds of inactive material.

With a given load applied having a loss of (W) watts for a time (t) the following statement is true:

Total Energy = stored energy + dissipated energy. (1)

But (a) Total energy = $W\,t$

(b) Stored energy = $0.06\,(P_a + r\,P_i)\,(T_t - T_s)$

Note: 0.06 is amount in watt-hours necessary to raise one pound of iron one deg. cent. based on a specific heat of 0.1135.

(c) Dissipated energy

$$= \int_0^t S_e K_e\, r\, T_t\, d\,t + \int_0^t S_i K_i\, (T_t - T_a/2)\, d\,t$$

(d) But $S_i K_i\,(T_t - T_a/2) = T_a V/1.8$
$= 0.555\, T_a V.$

Note: 0.555 is amount in watt-min. required to raise one cu. ft. of air one deg. cent.

(e) Hence $T_a = \dfrac{2\,S_i K_i T_t}{1.11\,V + S_i K_i}$

(f) Substitute (e) in (c) dissipated energy

$$= \int_0^t T_t \left(S_e\, r\, K_e + \frac{V\,S_i K_i}{V + 0.9\,S_i K_i}\right) d\,t$$

Substitute (a), (b), and (f) in (1)

$$W\,t = 0.06\,(P_a + r\,P_i)\,(T_t - T_s) + \int_0^t \left(S_e\, r\, K_e + \frac{V\,S_i K_i}{V + 0.9\,S_i K_i}\right) T_t\, d\,t \qquad (2)$$

Taking the derivative of (2) with respect to t;

$$W = 0.06\,(P_a + r\,P_i)\,\frac{d\,T_t}{d\,t} + \left(S_e\, r\, K_e + \frac{V\,S_i K_i}{V + 0.9\,S_i K_i}\right) T_t \qquad (3)$$

or

$$\frac{0.06\,(P_a + r\,P_i)\,d\,T_t}{W - T_t\left(S_e\, r\, K_e + \dfrac{V\,S_i K_i}{V + 0.9\,S_i K_i}\right)} = d\,t \qquad (4)$$

$$\text{Let } D = S_e\, r\, K_e + \frac{V\,S_i K_i}{V + 0.9\,S_i K_i}$$

$$\text{Hence } \frac{0.06\,(P_a + r\,P_i)\,d\,T_t}{W - D\,T_t} = d\,t \qquad (5)$$

The integral of this equation is

$$\int_{T_s}^{T_t} \frac{0.06\,(P_a + r\,P_i)\,d\,T_t}{W - D\,T_t} = \int_0^t d\,t \qquad (6)$$

$$\text{or} \quad \frac{-0.06\,(P_a + r\,P_i)}{D} \log_e (W - D\,T_t) \Big]_{T_s}^{T_t} = t \Big]_0^t$$

$$\text{or} \quad \frac{0.06\,(P_a + r\,P_i)}{D} \log_e \frac{W - D\,T_s}{W - D\,T_t} = t \quad (6a)$$

$$\text{or} \quad \frac{W - D\,T_s}{W - D\,T_t} = e^{\frac{D\,t}{0.06(Pa + rP_i)}}$$

$$\text{or} \quad \frac{W - D\,T_t}{W - D\,T_s} = e^{-\frac{D\,t}{0.06(Pa + rP_i)}} \quad (7)$$

When t = infinity $T_t = T_e$
Hence $W - D\,T_e = 0$
or $T_e = W/D$

$$= \frac{W}{S_a\,r\,K_a + \dfrac{V\,S_i\,K_i}{V + 0.9\,S_i\,K_i}} \quad (8)$$

$$\text{Let } t_1 = \frac{0.06\,(P_a + r\,P_i)}{D} = \frac{0.06\,(P_a + r\,P_i)\,T_e}{W} \quad (9)$$

Substitute (8) & (9) in (6a) $t = t_1 \log_e \dfrac{(T_e - T_s)}{(T_e - T_t)}$ (10)

$$\text{or} \quad t = 2.3\,t_1 \log_{10} \frac{T_e - T_s}{T_e - T_t}$$

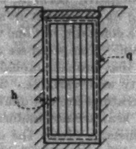
The above can also be expressed as

$$T_t = T_e - (T_e - T_s)\,e^{-t/t_1} \quad (11)$$

Where (e) is the Naperian base (2.718)

PART II

The above equations (10 or 11) will also apply to the heating of armature or field copper where the factors are defined as given below. A uniform copper temperature is assumed.



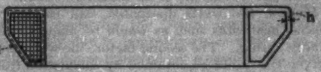
W = Total imbedded copper loss.
T_e = Final copper rise above iron.
T_t = Copper rise above iron at time (t).
t = Time in hours load is applied.
T_s = Copper rise above iron at start.

$$T_e = \frac{W\,h}{S_i\,K_i} \quad (12)$$

Where h = Insulation thickness inches.
S_i = Mean slot periphery (q) × No. of slots × core length.
K_i = Thermal conductivity of insulation in watts/sq. in./deg. cent.
Varies from 0.0025 to 0.0035.

$$t_1 = 0.05\,\frac{P\,T_e}{W} \quad (13)$$

When P = Equivalent pounds of copper of winding considered.
= 0.32 (volume of copper + 1/4 volume of insulation[1] in cubic inches)



For field winding the same terms are used except as noted below:
W = Total field copper loss.
T_e = Final copper rise above outside surface.
T_t = Copper rise above outside surface at time (t).
T_s = Copper rise above outside surface at start.
S_i = Length of mean coil turn × periphery (q) × No. of coils.

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[1] The factor 1/4 is used since the insulation has approximately 1/2 the thermal capacity of copper for the same volume and the insulation rise above its outside surface is 1/2 that of the copper.

Discussion

M. R. Hanna: Mr. Luke has shown the difficulty of calculating accurately the temperature of the various parts of a motor when operating on an intermittent duty cycle. However I would like to point out that it is possible to obtain quite satisfactory results without any great difficulty by considering larger sections of the motor. In the case of inclosed or slightly ventilated motors we can consider the motor as a whole and in the case of well-ventilated motors we may consider the armature as a whole and each of the field windings as separate units.

After we have calculated the losses in the motor under the various conditions of load, then if we know the watts that the motor or its various parts will dissipate at any given temperature rise and the watt-hours that it absorbs in attaining this temperature rise we can, by a simple calculation, obtain the temperature rise at the various points of the duty cycle. The ratio of these two quantities, the watts dissipated and the watt-hours absorbed is practically constant for any particular motor or part of motor under any given conditions of ventilation. This ratio definitely fixes the rate of heating or cooling. By rate I mean the time required to reach a given percentage of the ultimate temperature change. The relation is the simple logarithmic equation with which we are so familiar in its application to the rise of current in an inductive circuit. The first of these factors, the watts dissipated, can be determined from continuous heat runs such as would be made to determine the continuous rating. The second factor, the watt-hours absorbed for a given rise could be obtained by calculation from heat runs such as Mr. Luke suggests as a measure of the thermal capacity or may be calculated from the weight of material. If we are considering the motor as a whole it is surprising how good a value for the thermal capacity can be obtained simply from the weight of the bare motor. To illustrate this point I have taken values from Mr. Luke's table of distribution and disposal of losses in railway motors. In the columns for one-hour runs we find values for watts loss per pound of motor and also a value for the per cent absorbed. Now if we multiply these two values together we have, the watts absorbed per pound of motor during the one-hour run or the watt-hours absorbed per pound of motor for 75 deg. rise.

This multiplication gives the following results:

60 h. p. inclosed motor	1.96
65 h. p. self-ventilated motor	2.28
25 h. p. self-ventilated motor	1.85
200 h. p. separately ventilated motor	1.93

The average of these values is 2.01 watt-hours per pound. Note that the table covers a wide range of designs from 25 to 200 h. p. inclosed, self-ventilated and separately ventilated. The maximum variation from the average is only 13 per cent. This is fairly close for a quantity of this nature which is rather difficult to determine accurately and which is to be used, as Mr. Luke points out, in an equation based upon the assumption of a more uniform distribution of heat than actually exists. Incidentally this average value of watt-hours per pound of motor from Mr. Luke's table checks almost exactly with a value of two watt-hours that I have used for the past ten years in rough calculations of duty cycles in railway service.

In his conclusions Mr. Luke states that temperature limitation in railway service is found in the hot-spot temperature at peak loads. While this is a perfectly logical conclusion from the calculations presented, there are certain practical considerations that should not be overlooked. Time as well as temperature is an important factor in the deterioration of insulation. It is a matter of general knowledge that cotton when properly impregnated as required to meet the conditions of Class A material will stand temperature considerably in excess of that specified for Class A material for many days without serious deterioration. In an application where weight of equipment is of such great importance and where peak loads of such severity occur as in railway service it would not be economically correct to limit hot-spot temperatures at peak loads of short duration to the temperatures prescribed for continuous service. We must make some allowance for the element of time.

C. J. Fechheimer: I believe that one of the most interesting things in connection with various physical phenomena is that the equations which are derived for one kind of phenomenon apply to another; for instance, the equation for the magnetic field or for the electrostatic field are known to be very similar and practically identical. I refer to the flow lines and equal-potential lines. The gravitation field, the heat flow field, the hydrodynamic field pertaining to the flow of fluids, are mathematically at least, the same kinds of phenomena.

The particular case in point, in connection with Mr. Luke's paper, is his time-temperature curve equation, which is similar to that of the equation pertaining to the building up of current in an inductive circuit.

Mr. Luke's equation, (using his symbols) is, if the datum for reference be taken as T_s, (that is, T_s is taken as zero for reference): $T_t = T_e\,(1 - \epsilon^{-\frac{t}{t_1}})$
The time constant, $1/t_1$, is:

$$1/t_1 = \frac{S_e\, r\, K_e + \dfrac{S_i\, K_i}{1 + \dfrac{0.9\, S_i\, K_i}{V}}}{.06\,(P_a + r\, P_i)}$$

The first term in the numerator represents the watts dissipated from the external surface per degree. The second term will also be seen to increase with the watts loss.[1]

Therefore, the numerator is a factor which is nearly proportional to the watts liberated. The denominator is a constant—depending upon the specific heat times the weights. Therefore, the denominator represents the heat stored. In other words, the time constant, $1/t_1$, is equivalent to the ratio of the energy consumed to the energy stored.

The well-known equation for the growth of electric current in an inductive circuit is:

$$i = I_0\,(1 - \epsilon^{-\frac{r}{L}t})$$

This equation is in every way similar to Mr. Luke's equation as written above, provided the time constant R/L is similar to the time constant $1/t_1$. This will be seen to be the case, for R/L represents the ratio of the energy consumed indicated by R, to the energy stored in the magnetic field, indicated by L. Thus, i, the current at any instant, is comparable with T_t, the temperature at any instant; I_0 and T_e are comparable, both being the values for the steady state.

I want to call attention to the fact, mentioned also by Mr. Luke, that equations of this character can be considered only as approximate. I want to emphasize that point, so that any one using such equations would not be likely to be misled. The conditions might be compared, perhaps, with those which would obtain in the building up of current in an inductive circuit, if the factor L were not a constant, but one which depended on the permeability of the iron. You could see at once how extremely difficult a solution of that problem would be in the electric circuit if the permeability were variable. Some of the uncertainties are that the temperatures are not uniform, and therefore the rates of dissipation of heat are not uniform. We get all values of temperature, for instance, from the outside surface of the motor. Non-uniform temperatures also mean that there are complex internal heat flows—flows from high to low temperatures—which complicate the problem tremendously. Such factors it is next to impossible to incorporate in any mathematical derivations.

The constants entering into the equations are quite uncertain; such as the rates of dissipation of heat from any one of the surfaces. That nominal constant is very much complicated by the effect of eddies in the air. If the air moves in perfectly straight lines, it does not pick up nearly so much heat for a given rise of temperature of the surface above the air as it does if the air is highly turbulent. When highly turbulent, each particle of air comes into contact with the dissipating surface, and therefore each particle serves directly to pick up heat; otherwise, only those particles of air which come into contact with the particular surface are heated directly; with smooth flow, some particles are heated indirectly, that is, by conduction.

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[1] If 1 be neglected, the second term becomes simply V/0.9.[a constant for a given machine.] If the other term be ignored, the second term becomes $S_i\,K\,l$, = watts liberated from the internal ventilating surface.

As time goes on, as the air-heats,—the mass of air must necessarily decrease, assuming that the volume of air is constant; and as the amount of heat which the air can take up is a function of the mass of air per minute which passes through the motor, the air becomes less effective for carrying away the heat.

Again, the ratio "r" which Mr. Luke has in his equations, is also subject to experimental determination, and a great many tests are required before it can be determined with sufficient accuracy.

However, I do not want, by any means to disparage the value of Mr. Luke's paper, as I think it is quite a valuable contribution. As a matter of fact, the duty cycle of the railway motor is very uncertain; much more so than the factors which come in in the determination of the time-temperature curves. We can approximate sufficiently close for ordinary use, by means of Mr. Luke's equations, the conditions which obtain in general service in railway motors.

I think that if a complete solution were obtained it would be advisable to estimate roughly the influence of longitudinal heat flow in the copper, as well as the transverse heat flow. I attempted to do this in a paper which I read a year ago before the Institute.[2] That solution covers the steady state only; if, in addition, time is considered as an independent variable, the equations become so complicated that a solution is well nigh impossible.

I want to mention two more points; first, the enormous influence of air pockets. This was spoken of in discussing Mr. Shanklin's paper. In the insulating wrappers on coils, whether paper, or cloth, or mica, or what not, there are certain values of thermal conductivities for the individual layers of insulation. If these layers of insulation are put one above the other, as in ordinary practise, it is impossible to avoid tiny air pockets between them. The effect of these air pockets, (or "contact resistance"), is to decrease the thermal conductivity to about half the value which would obtain for the individual layers. This means, of course, that it is far more difficult for the heat to escape as the result of these air pockets than would be the case if they were not present. Furthermore, this decrease in thermal conductivity, due to the voids, makes the determination of temperature more uncertain because the thermal conductivity has a more uncertain value in wrappers, than when the individual layers alone are dealt with.

The other point: We are accustomed to speak of heat dissipated from machinery, or from any other heated body, as radiation. We speak, for instance, of those devices which are the agents for heating our rooms as radiators. As a matter of fact, nearly all the heat is dissipated from them by free convection currents, and only a little by radiation, radiation pertaining to heat waves in the ether. The heat which escapes from the incandescent lamp filament is almost entirely by radiation, because the temperature of the filament is so very high compared with the surrounding bodies, but not so with the heat from an electrical machine. There it is almost entirely dissipated by convection currents. Why should we not speak of the surfaces from which heat is dissipated as "heat-dissipating surfaces" rather than as "heat-radiating surfaces?"

F. W. Peters: From experience I feel that the designing engineers have pretty well mastered the subject of railway motor heating, the topic under discussion in the paper. This is borne out from a practical standpoint by the fact that there are relatively few failures emanating from straight overheating where motors are operated within the service for which they are recommended. Design constants are well known and a reasonable factor of safety used in application to motors with the result that the pure heating situation seems to be quite well taken care of.

However, I wish to read a sentence in Mr. Luke's paper as follows: "Railway motor failures may be classed as mechanical and electrical. A large part of electrical failures is due to poor commutation and flashing or to excessive temperatures."

On the basis of experience with failures of railway motors from a manufacturer's standpoint, it appears that failures because of excessive temperatures are relatively very few in number. Often it is difficult to determine the cause of a failure, and many times erroneous conclusions may be arrived at, because evidence of the primary cause for the failure may be destroyed. A failure, apparently due to temperature, is very often the result of a contributing cause initiated by a mechanical failure. For example, if a coil becomes loosened in a slot and mechanical chafing of the insulation results in an electrical breakdown, it is possible to attribute the failure to excessive temperatures, whereas it is primarily a mechanical failure.

Railway motors are subjected to very severe service with respect to operating under conditions of moisture. We are all familiar with the fact that failures in winter are much greater than in summer. Put two similar motors in equivalent service with one operating under severe moisture and the other under dry condition, the former motor would be expected to fail in a shorter time than the latter because of water and the dirt carried with it which more rapidly harms the insulation. While the heating conditions for the two motors are identical we would expect shorter life on one than the other because of an outside contributing cause. When such a motor fails it may be attributed to excessive temperatures, whereas it may in reality be due to the severe mechanical conditions to which the insulation has been subjected.

Other failures that we have to contend with are those caused by flashing which may harm the insulation, and on the occasion of a burnout may make it appear that excessive temperature was the cause; whereas the failure was accelerated by an abuse of the insulation.

A. C. Lanier: Mr. Luke's paper has brought out in a very interesting fashion the possibility of approaching what is rather a complex problem in a rational way, and getting results which are simple and yet dependable within reasonable limits. When conditions affecting heat dissipation are known, such as the losses and their distribution, the weights of material which absorb the heat energy, the volume of cooling air available, and the extent and character of the surfaces with which that air comes in contact, probable temperature rises may be predicted under known sets of conditions.

The same method of approach would very naturally suggest itself for motors in ordinary industrial applications, but with the ordinary industrial motor, some difficulties enter which are absent or less pronounced in the case of the railway motor. Of course, there is relief, on the other hand, from a good many difficulties which the railway service imposes. If we consider, for example, the open motor with natural ventilation, we find considerable variation in the ventilating characteristics even of individual machines of the same general line. For example, there is a difference in the effectiveness of multiple turn coil and single turn coils; this difference seems chargeable both to unequal fanning action, and unequal amounts of coil end surface exposed to the convection currents of air. Frequently with different motors and different coils, the flow of air is not found with any great degree of definiteness, it is very variable,—you might find different parts of the motor resisting rather than contributing to a definite air flow.

When the question of degrees of enclosure is introduced, the problem of ventilation and temperature rise is further complicated and is rendered still less definite. With total enclosure, the total external radiating surface of the motor sets a fairly definite limit to the losses which may be dissipated. With partial enclosure there is not only a reduction in the amount of cooling air carried into the motor, as compared with the open type, but its direction of flow may also be considerably modified.

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[2] Longitudinal and Transverse Heat Flow in Slot-Wound Armature Coils, TRANS. 1921, A. I. E. E. p. 589.

I should think, however, that though a larger number of constants might be necessary in applying these general relationships, which Mr. Luke has given to the ordinary industrial motor with natural ventilation, still with sufficient experimental data, his method might work out very well. I should like to know whether Mr. Luke has extended his investigations into the field of motors in industrial applications.

G. E. Luke: Mr. M. R. Hanna has shown that the watt-hours absorbed by the motor at the one-hour rating are approximately equal to two watt-hours per pound of motor and is practically independent of the type or degree of ventilation. Mr. Hanna mentioned the fact that insulation life is affected by not only high temperatures, but also by the time these temperatures existed. This point is well taken, since tests have been made under load conditions which caused the insulation to "smoke," involving temperatures ranging from 175 to 200 deg. cent for a few minutes duration. Examination of the insulation (Class A) showed it to be still in good condition. However, there is no doubt but that continued application of these high temperatures would soon cause failure. For example, tests on Class A insulation at 150 deg. cent. for three months rendered it lifeless as far as mechanical strength is concerned.

The poor thermal conductivity of insulating materials due to air pockets in the built up material was mentioned by Mr. C. J. Fechheimer. Proper impregnation of the insulation will reduce these high resistance paths to the flow of heat. Dipping and baking of the armature and fields is also beneficial in making the insulation more compact and homogeneous.

As stated by Mr. Fechheimer, radiation plays a minor part in the cooling of electric motors. For example the factor of 0.013 has been previously given as the watts *dissipated* from the external surface of a railway motor frame in watts per square inch per deg. cent. rise. This is the resultant of radiation, natural convection and a very small factor due to conduction through the motor supports. Of this constant (0.013) 20 to 30 per cent is due to radiation, and the remainder is mostly the resultant of natural convection.

Mr. F. W. Peters brought out the fact that a relatively small percentage of failures is caused by roasting or excessive heating of the insulation. Fortunately this fact is true especially when the motors are not loaded beyond the limits recommended by the manufacturer, and when weather conditions are not abnormal.

However many cases develop where a motor must be overloaded in order to maintain the schedules in an emergency. It should be clearly understood that on such abnormal overloads if failure occurs it is apt to be due to overheating since the factor of safety used from a mechanical standpoint is much greater than that feasible from the heating standpoint.

The purpose of this paper was to bring out the temperature limitations of the motor under different load conditions so that the lightest motor economically possible, consistent with satisfactory operation, could be used.

Prof. Lanier asked whether the method of calculation of temperature could be applied to industrial motors. The method as mentioned in the paper is more applicable to separately ventilated motors, where the air conditions are more definite, since the air is restrained to move in more or less definite paths. In the case of industrial motors where the machine is cooled by natural convection currents or the fanning action of the armature ducts and end windings, the conditions of ventilation are not definite enough to calculate with any degree of accuracy, from the fundamental physical conditions. However, if one continuous rating is known, other ratings on the same machine may be calculated at different loads and speeds as explained in the paper for self-ventilated motors.

The "Indumor"

A Kinematic Device which Indicates the Performance of a Polyphase Induction Machine*

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Subject of the Paper.*—A kinematic device is described and illustrated which represents the vector diagram of a polyphase induction machine. The parts are made to assume at will different positions corresponding to different loads of an induction motor or generator. The primary and the secondary constants, the magnetizing current, and the core loss, are also adjustable at will. The device permits the visualization of the performance of an induction machine and can be used for a study of a given machine or for a selection of the constants to give the desired performance characteristics of a new machine. The input, output, torque, speed, power factor, etc., can be read off on the device as in an actual brake test.*

The kinematic connections consist mainly of generalized proportional dividers and of parallel tongs, so combined as to satisfy a system of simultaneous vectorial equations which represent the properties of the machine. Further applications of the device to polyphase commutator motors are suggested.

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Introduction—What the Indumor is. (85 w.)
Purpose of the Device. (175 w.)
Performance Curves which the Indumor Enables one to Draw. (35 w.)
Factors which may be taken into Account. (35 w.)
Limits of Rating and Output. (120 w.)
General Description of the Indumor. (500 w.)
Principal of the Indumor. (250 w.)
Performance Diagram of a Polyphase Induction Motor. (1200 w.)
Kinematic Details of the Indumor. (50 w.)
    I. Proportional Dividers for the Primary Impedance Drop. (500 w.)
    II. Proportional Dividers for the Secondary Reactive Drop. (350 w.)
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INTRODUCTION

The Meaning of the Word "Indumor." An abbreviation of the words "induction motor."

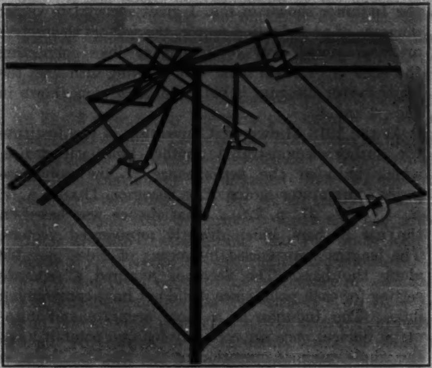

FIG. 1—THE INDUMOR

What the Indumor is. A combination of movable and adjustable bars (Fig. 1) which can be set to represent to a certain scale a vector diagram of voltages, currents, m. m. fs. and fluxes in a polyphase induction motor or generator of any desired constants. The parts of the device are kinematically so constrained that the diagram set correctly for one load remains correct at any other load.

The Purposes of the Device. (1) To enable a designer to select the best electrical constants and to "test" an induction motor or generator before it has been actually built. (2) For some applications to take the place of an involved analytical theory; it is often difficult to see the effect of separate factors upon the performance characteristics, and it takes considerable mathematical skill to deduce the equations of the various loci. (3) For some purposes to take the place of the circle diagram which becomes quite complicated when the primary resistance is taken correctly into consideration. (4) To add the judgment of the eye and the skill of the hands to the purely mental ability in selecting the constants of a machine for a desired performance, or in judging the characteristics for assumed constants. (5) To enable an investigator or a student to familiarize himself with the machine as if he had one available for tests. This is of particular importance with large machines for which no facilities may be available for testing.

The Performance Curves that the Indumor Enables One to Draw. Current, torque, speed, slip, input, output, efficiency, power factor, and magnetizing current. These may be obtained just as easily at a constant applied voltage as at a voltage which varies in any desired manner.

The Factors Which May be Taken into Account and varied separately at will in the Indumor. Per cent magnetizing current; per cent primary and sec-

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Presented at the 10th Midwinter Convention of the A. I. E. E., New York, N. Y., February 15-17, 1922.

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ondary resistance; per cent primary and secondary reactance; core loss; friction.

Limits of Rating and Output. Like any other graphical device, the Indumor requires certain scales to be chosen for each particular problem. A convenient scale has to be selected for amperes, and another for volts. The device can represent the performance of a fractional horse-power motor as well as of one whose output runs into thousands of kilowatts; of a 110-volt machine as well as of one wound for 11,000 volts. As in any graphical device, there are limitations due to a finite length of the links. With a certain setting the device may give an accurate performance say between no-load and 1.5 times the rated current. If a heavier overload is desired a smaller scale may have to be chosen for amperes.

B. General Description of the Indumor

The first complete Indumor was built in the shops of Cornell University during the summer of 1921 and is shown in Fig. 1. The same device is shown as a single-line diagram in Fig. 8. It is made of flat steel bars, not over one cm. wide and a few millimeters thick. The lengths of the principal members, between centers, in centimeters, are shown in Fig. 8. Some bars are of constant length, others are of adjustable useful length, holes being drilled every few millimeters. Most bars are connected to each other by means of pivot joints; others are set at a constant angle to each other by means of the protractors clearly seen in Fig. 1.

The device is assembled on a table provided with two grooves, at right angles to each other. The ends of some bars are constrained to move in these grooves. Different bars have to be placed in different horizontal planes to enable them to cross each other without interference. In Fig. 8 the bars nearest to the table are marked 1, those immediately above them are marked 2, etc. The particular sequence selected is not essential since the device is intended to represent a vector diagram in a plane.

A detailed description of the functions of different parts is given below in connection with the theory of the Indumor. It suffices to state here that the device is set for chosen design constants at a certain load. The setting is done by selecting suitable scales for volts and amperes and adjusting the lengths of a few bars and the angles accordingly. The Indumor then represents a set of four simultaneous vectorial equations which together characterize the machine, viz.:

(a) The primary electric circuit;

(b) The secondary electric circuit;

(c) The main magnetic circuit;

(d) The relationship between the induced e. m. f. the flux.

After having been properly set, the kinematic combination becomes a *system with one degree of freedom*, that is, if any point of it is moved, all other points move in a perfectly definite manner. It is well known that an induction motor at a constant applied voltage is such a system. As the load varies, all the electrical characteristics and the speed vary in only one possible way. It differs in this respect from a shunt-wound direct-current motor in which the field current is a second independent variable, or a second degree of freedom.

Having set the device, the lower knob is moved up and down in the groove. This causes all other members to assume new positions. For any position of the knob readings can be taken of the current, phase angle, torque, slip, output, etc., as in any brake test. Lengths are measured with an ordinary meter scale, and phase displacements may be either measured directly with the sighting goniometer shown in Fig. 9, or computed from the measured projections of vectors, as is explained below.

The Principle of the Indumor. The device is based on the principle of ordinary dividers. Let the two legs on a pair of dividers be denoted $A\,B$ and $B\,C$, with the pivot at B. The length to be measured is AC, and $A\,C$ can be varied at will by opening or closing the dividers, even though the length of the dividers' legs is constant.

Similarly in the Indumor the variable vectors are not represented by the bars themselves, but by the distances between the ends of two bars. The only vector directly represented by a bar is that of applied voltage because it remains constant. Thus, while the Indumor shown in Fig. 1 gives a complete vector diagram of an induction motor, the vectors themselves are represented only by imaginary lines connecting the ends of various bars. By drawing such lines the usual vector diagram is obtained, such as is shown in Figs. 3 and 4.

At the 1918 Midwinter Convention of the Institute the author demonstrated another kinematic device, which imitated the performance of the polyphase series commutator motor (The Secomor, Trans. A. I. E. E., Vol. 37, p. 329). That device was based on the use of bars which directly represented vectors. The lengths were varied by means of slides movable along the bars. The Secomor required a separate setting for each point since it did not have constraining links. The Indumor is a more accurate and automatic device; once set correctly for one point it gives the whole range of operation of the machine, because of properly designed constraining motions.

The Performance Diagram of a Polyphase Induction Motor

It is well known that for certain purposes a polyphase induction motor may be replaced by an equivalent combination of resistances and reactances, as shown in Fig. 2 (see for example the author's "Electric Circuit", Chap. XII). In this diagram one phase only is represented; r_1, x_1, r_2, and x_2, are the primary and the secondary resistances and reactances, the secondary quantities being reduced to the primary circuit, (see for example the author's "Magnetic

Circuit", p. 133). The susceptance b_0 is of such a magnitude that the current I_m passing through it is equal to the actual magnetizing current of the motor. The conductance g_0 causes a joulean loss numerically equal to the primary core loss of the actual machine.

The mechanical load of the actual machine is replaced by an adjustable resistance R; the $I_2^2 R$ loss in this resistance can be made equal to a desired motor load. Strictly speaking, this load, in addition to the useful output, includes the friction, windage, and the secondary core loss. In approximate computations the friction and windage losses are sometimes taken into account in the conductance g_0, but it is better to subtract the mechanical losses from the total output. A still better approximation to the actual conditions could probably be obtained by using three shunted constant conductances, one across the line terminals A B, one across M N, and one between C and D.

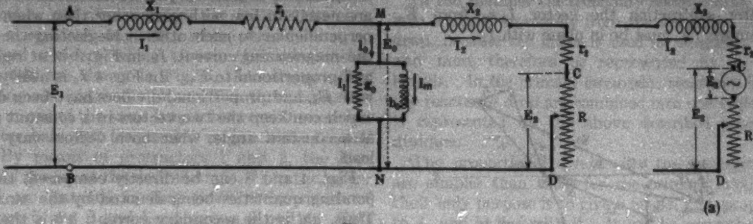

FIG. 2

A combination of resistances and reactances shown in Fig. 2 gives nearly the same performance curves as the actual motor. Let a certain brake load be applied to the actual motor and let the resistance R of the equivalent combination be so adjusted that the primary current is the same as in the actual motor. Then it will be found that the primary input and the power factor are also the same and that the brake load is equal to $I_2^2 R$ watts, less the friction and windage.

The slip, being equal to the percentage of secondary loss, can be computed as the ratio of r_2 to $(R + r_2)$, and checks very closely with the actually measured slip. The torque, in synchronous watts, is equal to the input into the secondary circuit and therefore is equal to $I_2^2 (R + r_2)$. The voltage E_0 between M and N is a measure for the air-gap flux. Thus, all the important characteristics of the motor can be obtained from the equivalent diagram, either by test or by computation.

For the operation as an induction generator, above synchronism, the resistance R should be assumed negative. At synchronism this resistance is infinitely great, and in the transition from motor to generator it jumps from $+ \sim$ to $- \sim$. Then it remains negative, decreasing in its absolute value. Another way of representing the generator range is to replace the resistance R by a counter-e. m. f. E_2. At synchronism E_2 must be equal and opposite to the voltage E_0 between M and N in order to reduce the secondary current to zero. As the generator load increases, E_2 must be made greater than E_0, always keeping E_2 in phase with the scondary current, I_2, which is now reversed.

The Vector Diagram. The relationships shown in Fig. 2 are represented vectorially in Fig. 3, which is the familiar transformer diagram at non-inductive load. Beginning with the vector of the air-gap flux, the magnetizing current, I_m, is drawn in phase with it and the core loss component, I_1, in quadrature with it. This gives the total exciting current, I_0, through the shunted admittance between M and N in Fig. 2. This current leads the flux by an angle α.

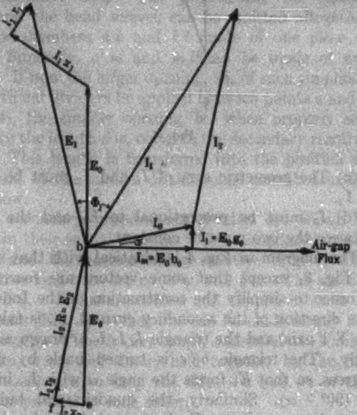

FIG. 3

The voltage E_0 balances the e. m. f. induced by the air-gap flux, and is therefore drawn in leading quadrature with it. The applied voltage consists of E_0 and of the parts $I_1 r_1$ and $I_1 x_1$ lost in the primary impedance. The voltage E_0 is used up in the secondary circuit, partly in the impedance of the winding, partly in the resistance R. The primary current, I_1, is equal to the secondary current, I_2, plus the exciting current I_0.

We thus have the following four fundamental vectorial relationships which must be simultaneously fulfilled in the Indumor:

(a) The geometric sum of E_0, $I_1 r_1$, and $I_1 x_1$, must be equal to the applied voltage E_1.

(b) After subtracting the vector $I_2 x_2$ from E_0, the remainder, $f b$, must be in phase with I_2.

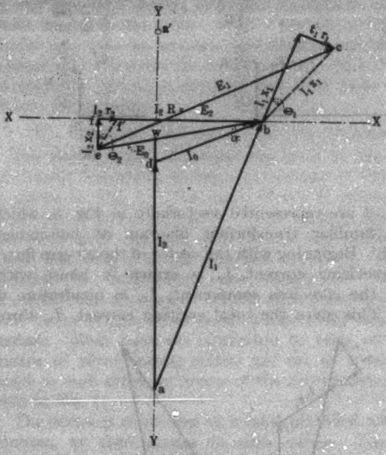

FIG. 4

(c) The geometric sum of I_0 and I_2 must be equal to I_1.

(d) I_0 must be proportional to E_0 and the angle between the two must be constant.

The diagram in Fig. 4 is identical with that shown in Fig. 3, except that some vectors are rearranged in order to simplify the construction of the Indumor. The direction of the secondary current, I_2, is taken as the $Y\,Y$ axis, and the triangle $I_2\,I_0\,I_1$ is drawn accordingly. The triangle $b\,f\,e$ is turned back by ninety degrees, so that E_0 forms the angle α with I_0, instead of $(90° - \alpha)$. Similarly, the quadrilateral built on the primary voltage E_1 is turned back by ninety degrees, and is so placed that E_0 is its common side with the triangle of secondary voltages. The vector $I_2 R = E_2$, which in Fig. 3 is parallel to I_2, is now perpendicular to I_2, and chosen as the direction of the $X\,X$ axis.

In Fig. 4, as well as in the Indumor, all the voltage vectors are turned back by 90 deg. with respect to their true positions in Fig. 3. Or else, the voltages in the Indumor may be said to be in their correct position, but the currents advanced in phase by 90 deg. This must be borne in mind when measuring the phase angle between the primary current and voltage. The operation of the device is not otherwise affected since the currents and the voltages form separate closed figures.

The reason for turning the voltages, or the currents, in the Indumor is that it is mechanically much simpler to make two lengths vary in a constant ratio when they are nearly in line with each other than when they are perpendicular to each other. Neglecting the core loss, the magnetizing current, I_0, in Fig. 3 is at right angles and proportional to E_0. In Fig. 4 I_0 is nearly in phase with E_0, and proportional dividers have been developed which can keep the two vectors in a constant ratio and at a constant angle, when both vectors vary with the load.

Figs. 4 and 8 can be directly compared, the corresponding quantities being denoted by the same letters. Thus, $a\,d$ is the secondary current, $a\,b$ is the primary current and $d\,b$ is the exciting current. The primary impedance drop is $b\,c$, the secondary reactive drop is $e\,f$, the applied voltage is $e\,c$, etc. Since the Indumor is based on the principle of dividers, all the variable vectors are measured between the pivot points of different bars and not along one and the same bar.

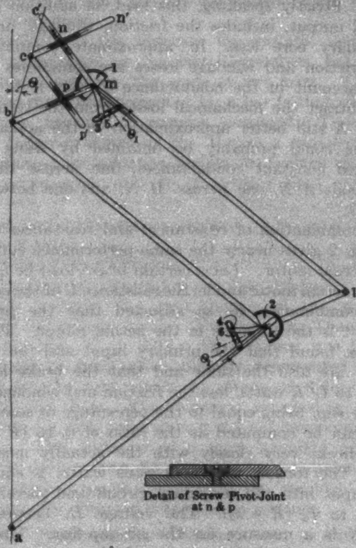

FIG. 5—PROPORTIONAL DIVIDERS

THE KINEMATIC DETAILS OF THE INDUMOR

Having established the relationship between the vector diagram in Fig. 4 and the linkages in Fig. 8, it remains to show how the various points are constrained to move along certain paths in order that the four above-mentioned conditions remain fulfilled with any setting of the device.

I. *Proportional Dividers for the Primary Impedance Drop*

In Fig. 4 the primary current, $I_1 = a\,b$, and the primary impedance drop, $I_1 z_1 = b\,c$, are proportional to each other and their vectors are inclined to each other at a constant angle θ_1, where $\tan\,\theta_1 = z_1/x_1$. Proportional dividers which permit this relationship to be realized are shown in Fig. 5, the corresponding points being also marked *a*, *b*, *c*. The three bars, *a k*, *b k*, and *l m*, are of the same length between the centers. The shorter bars, *k l*, *b m*, and *c′ m*, are also of equal length. By means of protractors 1 and 2, the bars *c′ m* and *k l* are set at the desired angle, θ_1, to the longer bars, and are fastened in that position by means of slotted bars 5 and 6 and head screws 3 and 4. This makes the triangles *b m c′* and *a k b* similar to each other, with their corresponding sides inclined at the angle θ_1 to each other. By opening or closing the dividers, the distance *a b* may now be varied at will, and the distance *b c′* will always remain proportional to it and inclined at the angle θ_1.

The desired length *b c* is different from *b c′*, and point *c* is located by means of the bars *c n′* and *c p′*, by making *b p* = *p c* and *c n* = *c′ n*. The holes in the upper bars are drilled and counter-sunk; those in the lower bars are drilled and tapped, as shown in the detail sketch. Machine screws are used at points *p* and *n* for fastening the bars together. These screws do not prevent a free rotation of the bars relatively to each other. The triangle *b p c* is similar to *b m c′*, so that *b c* also remains proportional to *a b*.

The bars *a k* and *k b* must be long enough to allow the dividers to be opened for the greatest length *a b* of the vector of primary current for which the Indumor is designed. The shorter bars must allow a setting for the highest percentage of primary impedance drop that will ever be used with the apparatus. To illustrate, let the total length of the bar *e c* (Fig. 8), which represents the primary applied voltage, be 150 cm., and let the highest primary impedance drop, that may ever be encountered under the extreme practical conditions, be say 10 per cent of the applied voltage. Then the length *b c′*, with the dividers fully opened, should be not less than 15 cm. Should a special motor have the primary impedance drop of over 10 per cent, it is only necessary to use a shorter length for the primary terminal voltage. For example, with the vector of primary voltage 75 cm. long, an opening *b c′* = 15 cm. corresponds to a primary impedance drop of 20 per cent. Any smaller value of primary impedance drop down to zero, can be obtained by properly setting the point *c*.

When adjusting the dividers it must be remembered that the reactive drop is set in phase with the current, and the ohmic drop in quadrature with it, because in the Indumor the currents are turned by 90 deg. with respect to their true position in Fig. 3. The dividers just described are denoted in Fig. 8 by the same letters.

II. *Proportional Dividers for the Secondary Reactive Drop*

In the Indumor the secondary reactive drop is taken into account separately from the secondary resistance drop, because the latter is used in measuring the slip and must therefore be represented by a separate length. In the primary circuit the resistance drop and the reactance drop are combined into one vector which is represented by the above described proportional dividers.

The proportional dividers for the secondary circuit are simpler than those for the primary circuit, since their only purpose is to give a length $I_2 x_2$ proportional to I_2 and in line with it. It will be remembered that in the Indumor the voltages are turned by 90 deg. with respect to their true position in Fig. 3, so that the reactive drop is in phase and not in quadrature with the current.

When the two protractors in Fig. 5 are set on zero, the segments *a b* and *bc* lie on the same straight line, and such a device can be used for the secondary current and reactance drop. The protractors, the slotted bars, and the head screws, can be omitted altogether and the members *a k* and *k l* made of one piece of steel. Similarly, *c′ m* and *m l* can be made of one piece. If now the larger opening, *ab*, of such simplified proportional dividers be applied between points *a* and *d* (Fig. 4), the smaller opening, *bc*, when properly set, will give the length *d w*, equal to the secondary reactive drop. This length is transferred into the position *e f* by means of the parallel double-tongs described under III below.

The secondary proportional dividers are shown in Fig. 8 in their actual position. The secondary current is *a d* and the corresponding reactive drop is *d w*. The three long bars are *a r*, *r w*, and *q d*. The shorter bar is *d u*. Holes are drilled and tapped in some of these bars (Fig. 1) so that *d w* can be made of any desired length. The dividers simply consist of two similar triangles, *a r w* and *d u w*, held together by the bar *q d* so as always to keep the sides *d u* and *a r* of the triangles parallel to each other.

III. *Parallel Double-Tongs*

The secondary reactive drop *d w* (Fig. 4) obtained by means of the proportional dividers, has to be transferred to the position *e f* at the end of the vector E_1. As the load varies, the distance between *d* and *e* also varies, both in magnitude and in direction, so that it is necessary to connect the points *d*, *w*, and *e*, by means of an adjustable translating device, whose fourth point would give the correct position of point *f*.

Such a device, which might be called "parallel double-tongs," is shown in Fig. 6 in two positions. The four end-points are lettered *d*, *w*, *e*, and *f*, to correspond to Fig. 4. The construction of the device is such that *f e* is always equal and parallel to *w d*. If *f e* be kept constant and stationary, the tongs will allow only such displacements of the points *w* and *d* at which the distance *w d* remains equal and parallel to itself, as shown by the dotted lines. If *f e* be varied in direction and in magnitude, *w d* will vary accordingly.

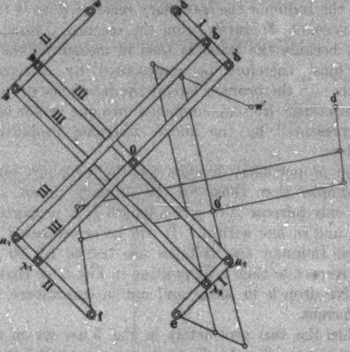

Fig. 6

The device consists of eight pivoted members. There are two short bars of equal length, marked *I*, two equal bars, *II*, of intermediate length, and four long bars, *III*, of equal length. The length *w w'* between the centers must be equal to *d d'*, and *w' w"* must be equal to *d' d"*. The pivot joint *o* must be at the center of both long bars which it connects. In other respects the dimensions of the device are arbitrary and depend upon the range of the distances which it is designed to cover. A given distance may also be connected between *f* and *w*, instead of between *f* and *e*, and an equal and parallel distance is then maintained between *e* and *d*.

The parallel double-tongs are shown in Fig. 8 between the points *d*, *w*, *e*, and *f*, and are marked with the same letters as in Fig. 6; they may also be seen in Fig. 1. In the actual use of the Indumor it has been found convenient to have two pairs of tongs, one for larger distances, when a long bar is used for the applied voltage, and one for shorter distances, for use on overloads and near the starting point of the motor, at a reduced terminal voltage. When the limit of one pair of tongs has been reached they are removed and the other pair is slipped in its place.

The proof of the parallel double-tongs is as follows: Let point *o* be kept stationary, and let point *f* occupy any desired position. The vectors *o f* and *o d* are equal and opposite because of the chosen lengths of the links. Similarly the vectors *o e* and *o w* are always equal and opposite; they are also independent of the other half of the device. Thus, the triangles *o f e* and *o w d* are equal and turned by 180 deg. with respect to each other. Hence, the vectors *f e* and *w d* are equal and parallel.

IV. *Proportional Dividers for the Magnetizing Current*

In Fig. 4 the magnetizing current, I_0, is drawn at a constant angle α to the voltage E_0. As the load varies, both E_0 and I_0 vary, but their ratio remains constant (neglecting magnetic saturation). As shown in Figs. 2 and 3, the value of the angle α is determined by the relationship

$$\tan \alpha = g_0/b_0 \qquad (1)$$

Generalized proportional dividers which permit I_0 and E_0 to vary while satisfying these conditions, are shown in Fig. 7. The lines *b d* and *b e* have the same meaning as in Fig. 4. By turning Fig. 7 by 90 deg so that point *b* is on top, it will readily be seen that these proportional dividers are practically identical with those shown in Fig. 5, except for somewhat different proportions. Therefore no new proof is needed for the fact that the triangle *e b d* remains similar to itself as the dividers are opened or closed. These dividers are shown in the assembly (Fig. 8) marked with the same letters as in Fig. 7.

The angle which corresponds to θ_1 in Fig. 5 is denoted by β in Fig. 7, and the protractors are set for this angle. It will be seen that angle β is different from the required angle α at *b*. Since the device is intended to represent angle α, it is necessary to know the relationship between α and β. This simple relationship may be obtained either graphically or analytically.

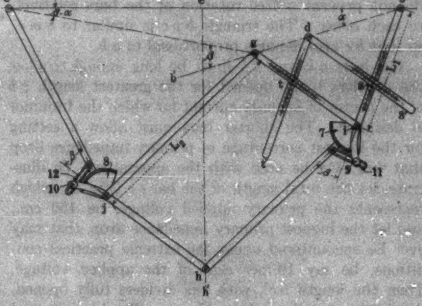

Fig. 7—Proportional Dividers

Graphical Solution. On a sheet of paper lay off any reasonable value of *e b* and draw the line *b b'* at the angle α to it. Also draw the perpendicular bisector *e' h'* to *e b*. Loosen the head screws 9 and 10, place the ends of the dividers on points *e* and *b*, place point *h* on *e' h'* and point *g* on *b b'*. The readings on

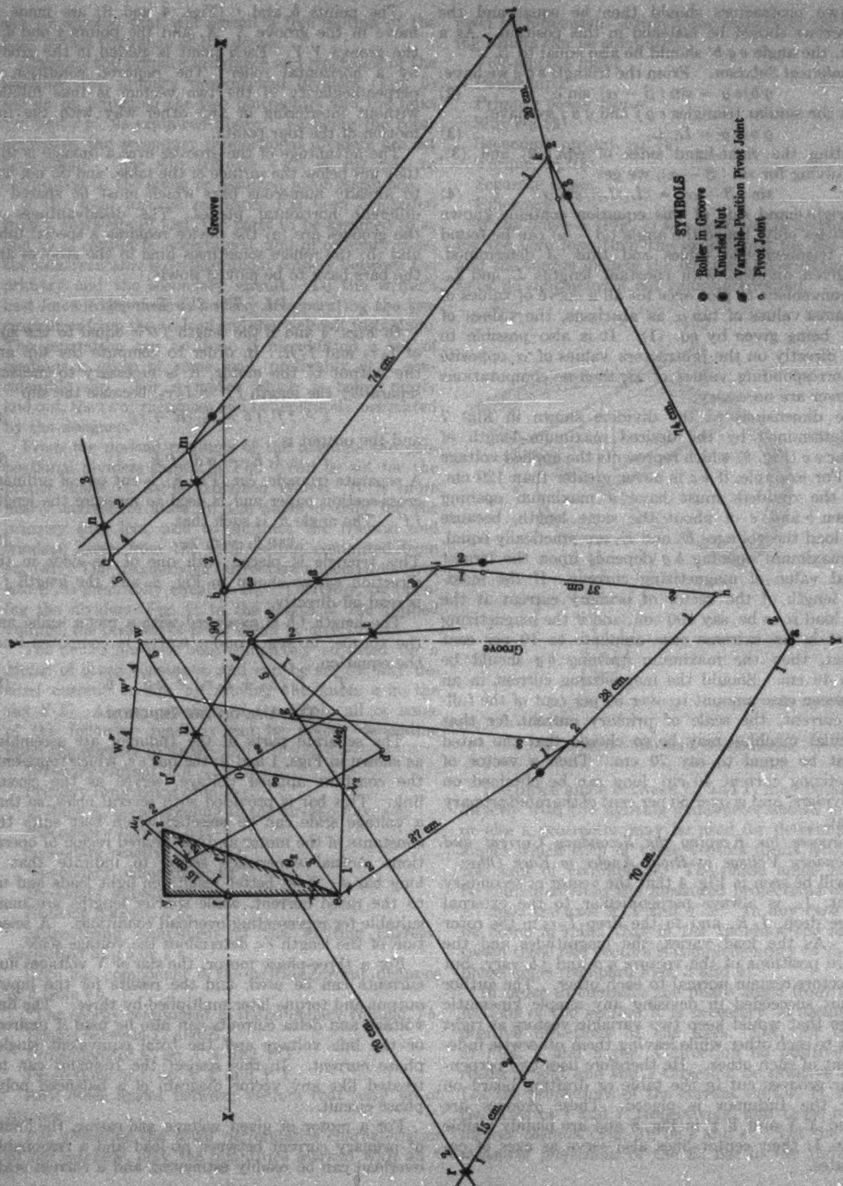
SYMBOLS
● Roller in Groove
● Knurled Nut
● Variable-Position Pivot Joint
○ Pivot Joint
Groove
Groove
X
X
Y
Y
74 cm.
74 cm.
74 cm.
20 cm.
37 cm.
28 cm.
87 cm.
70 cm.
70 cm.
15 cm.
90°

FIG. 8—SINGLE-LINE DIAGRAM OF THE INDUMOR

the two protractors should then be equal and the headscrews should be fastened in this position. As a check, the angle $e\,g\,b'$ should be also equal to β.

Analytical Solution. From the triangle $e\,b\,g$ we have:

$$g\,b/e\,g = \sin(\beta - \alpha)/\sin\alpha \tag{2}$$

From the similar triangles $e\,g\,j$ and $g\,b\,i$ we have:

$$g\,b/e\,g = L_1/L_2 \tag{3}$$

Equating the right-hand sides of eqs. (2) and (3), and solving for $\sin(\beta - \alpha)$, we get

$$\sin(\beta - \alpha) = (L_1/L_2)/\sin\alpha \tag{4}$$

The right-hand side of this equation contains known quantities only, hence the angle $(\beta - \alpha)$ can be found from trigonometric tables and thus β determined. For given dividers, with constant lengths L_1 and L_2, it is convenient to plot once for all a curve of values of β against values of $\tan\alpha$ as abscissas, the values of $\tan\alpha$ being given by eq. (1). It is also possible to mark directly on the protractors values of α opposite the corresponding values of β; then no computations whatever are necessary.

The dimensions of the dividers shown in Fig. 7 are determined by the desired maximum length of the bar $e\,c$ (Fig. 8) which represents the applied voltage E_1. For example, if $e\,c$ is never greater than 120 cm. then the dividers must have a maximum opening between b and e of about the same length, because at no load the voltages E_0 and E_1 are practically equal. The maximum opening $b\,g$ depends upon the largest desired value of magnetizing current. If the maximum length of the vector of primary current at the rated load is to be, say 100 cm., and if the magnetizing current in an extreme case amounts to 40 per cent of that, then the maximum opening $b\,g$ should be about 40 cm. Should the magnetizing current in an unforeseen case amount to over 50 per cent of the full-load current, the scale of primary current for that particular machine may be so chosen that the rated current be equal to say 70 cm. Then a vector of magnetizing current 40 cm. long can be obtained on the dividers, and is over 50 per cent of the rated primary current.

V. Grooves for Keeping the Secondary Current and Secondary Voltage at Right Angles to Each Other

It will be seen in Fig. 4 that the vector of secondary current, I_2, is always perpendicular to the external voltage drop, $I_2\,R$, and to the drop $I_2\,r_2$ in the rotor itself. As the load varies, the magnitudes and the relative positions of the vectors $a\,d$ and $f\,b$ vary, but the vectors remain normal to each other. The author has not succeeded in devising any simple kinematic linkage that would keep two variable vectors at right angles to each other while leaving them otherwise independent of each other. He therefore uses two perpendicular grooves cut in the table or drafting board on which the Indumor is placed. These grooves are marked $X\,X$ and $Y\,Y$ in Fig. 8 and are plainly visible in Fig. 1; their center lines also serve as axes of coordinates.

The points b and f (Figs. 4 and 8) are made to move in the groove $X\ X$, and the points a and d in the groove $Y\,Y$. Each point is guided in the groove by a horizontal roller. The required condition of perpendicularity of the two vectors is thus fulfilled without interfering in any other way with the free motion of the four points.

The advantage of the grooves over a linkage is that they are below the surface of the table, and do not add to already numerous bars which must be spaced in different horizontal planes. The disadvantages of the grooves are (a) the device requires a special table and (b) the rollers sometimes bind in the grooves and the bars have to be moved slowly.

VI. The Slip Triangle

In Figs. 4 and 8 the length $f\,b$ is equal to the sum of $I_2\,r_2$ and $I_2\,R$. In order to compute the slip and the output of the motor, it is necessary to measure separately the length $f\,f' = I_2\,r_2$, because the slip

$$s = f\,f'/f\,b = r_2/(R + r_2) \tag{5}$$

and the output is

$$P_2 = I_2\,E_2 = a\,d\,.\,f'\,b \tag{6}$$

A separate triangle, *eyz* (Fig. 8), is cut out of ordinary cross-section paper and is used to measure the length $f\,f'$. The angle θ_2 is such that

$$\tan\theta_2 = r_2/x_2 \tag{7}$$

This triangle is placed with one of its sides in the direction $e\,f$, as shown in Fig. 8, and the length $f\,f'$ is read off directly.

The length $f\,b$ is measured with a meter scale, and the torque, in synchronous watts, is computed from the equation.

$$T = I_2\,(E_2 + I_2\,r_2) = a\,d\,.\,f\,b \tag{8}$$

THE USE OF THE INDUMOR

The separate parts of the Indumor are assembled as shown in Figs. 1 and 8; the bar $e\,c$, which represents the constant applied voltage, serves as the closing link. This bar is provided with several holes, so that a voltage scale can be selected which best suits the constants of the motor and the desired region of operation. Actual experience seems to indicate that a long bar $e\,c$ gives better results on light loads and up to the rated current, while shorter lengths are more suitable for representing overload conditions. A selection of the length $e\,c$ determines the voltage scale.

For a three-phase motor, the star or Y voltages and currents can be used, and the results for the input, output and torque later multiplied by three. The line voltage and delta currents can also be used if desired, or the line voltage and the total equivalent single-phase current. In this respect the Indumor can be treated like any vector diagram of a balanced polyphase circuit.

For a motor of given voltage and rating, the limits of primary current between no-load and a reasonable overload can be readily estimated, and a current scale can be selected that will permit a free motion of the links within the range of the device.

Knowing the primary resistance and reactance of the machine, the primary proportional dividers (Fig. 5) are set by adjusting the two protractors and the links *c n'* and *c p'*, as explained above. Knowing the rotor reactance, the secondary proportional dividers are set accordingly. The slip triangle *e y z* is cut out to correspond to the given or assumed rotor resistance.

If the total leakage reactance has been computed from a short-circuit test, the parts to be assigned to x_1 and to x_2 cannot be ascertained, and in ordinary cases the total reactance is divided about equally between the primary and the secondary circuit. To the writer's best knowledge, there is no way of separating the two reactances from the no-load and short-circuit tests alone. The separation can be done if in addition a set of readings is given at some load, preferably at a considerable slip. For a motor which is being newly laid out, the two reactances can be separately estimated by the designer.

From the no-load readings of the machine the proportional dividers shown in Fig. 7 can be set for the proper angle α, as is explained above. It is more nearly correct to allow in the angle α only for the primary core loss, and to subtract the friction and windage losses from the total output computed from eq. (**6**). The magnetizing current at no-load is known, and E_0 is practically equal to E_1. Therefore, by opening the dividers (Fig. 7) to the length of the applied voltage, the position of point *d* can be ascertained.

The device has now been completely adjusted for a motor of given constants, and can be set for any desired current or slip by moving the knob, *a* in the slot *Y Y*. At any position of the knob, all or some of the following readings can be taken, depending upon the purpose in view:

*Primary current, *a b*.
Primary impedance drop, *b c*.
Voltage E_0 corresponding to the air-gap flux, *e b*.
*Secondary current, *a d*.
Secondary reactive drop, *e f*.
*Secondary ohmic drop, *f f'*.
Secondary impedance drop, *e f'*.
Exciting current, *d b*.
Magnetizing component of the exciting current, projection of *d b* on *e b*.
Core loss component of the exciting current, distance of *d* from *e b*.
*The energy component of the secondary voltage, *f b*.
*Angle between I_1 and E_1.
Projections of E_1 on *X X* and *Y Y*.
Projections of I_1 on *X X* and *Y Y*.
Any other angles between vectors that may be of interest.

For obtaining the usual performance characteristics of the machine, only the quantities marked with an * need be measured. From these quantities the following results can be computed:

Volt-ampere input
Power input
Primary power factor
Slip, eq. (**5**)
Secondary output, eq. (**6**)
Torque, eq. (**8**)
Separate losses
Efficiency.

If the angle α (Fig. 7) has been set to account only for the core loss, then the expressions for the output and the torque include the friction and windage which must be subtracted if net values aredesired.

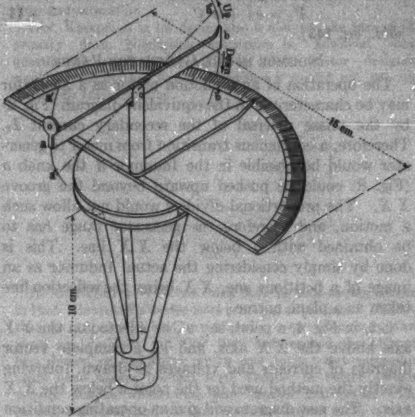

FIG. 9—SIGHTING GONIOMETER

The phase angle between E_1 and I_1 may be measured directly with the sighting goniometer shown in Fig. 9; or else a protractor may be used for determining the angles which each of these vectors forms with one of the axes of coordinates. The phase angle may also be computed from the measured projections of I_1 and E_1 upon the axes *X X* and *Y Y*. In any case it must be borne in mind that in the Indumor the angle between these two vectors is complementary to the actual phase angle (compare Figs. 3 and 4).

In order to compute the phase angle from the projections of the vectors it is necessary to assume some positive directions of the axes. Let, for example, in Figs. 4 and 8 the *X*-direction be positive to the reader's right and the *Y*-direction be positive upward. Let the projections of the current vector, I_1, on these two axes be *i* and *i'* respectively, and those of E_1, *in its true position* (Fig. 3), be *e* and *e'*. Let the *actually measured projections* of the E_1 bar in the Indumor be

E_x and E_y. We then have, by advancing E_1 by 90 degrees,

$$\left.\begin{aligned} e &= -E_y \\ e' &= E_x \end{aligned}\right\} \qquad (9)$$

The phase angle ϕ_1 is computed from the familiar formula

$$\tan \phi_1 = \frac{(e'/e) - (i'/i)}{1 + (e'/e)(i'/i)} \qquad (10)$$

See for example the author's "Electric Circuit," p. 91, eq. (**144**). The positive and negative signs of the projections must be carefully observed.

The power input can be computed either from the expression $E_1 I_1 \cos \phi_1$, or from the same projections of the vectors, using the formula

$$P_1 = e\,i + e'\,i' \qquad (11)$$

(*ibid.*, eq. **143**).

INDUMOR IN THE GENERATOR RANGE

The operation of an induction motor as a generator may be characterized in the equivalent diagram (Fig. 2) by the phase reversal of the secondary current I_2. Therefore, a continuous transition from motor to generator would be possible in the Indumor if the knob a (Fig. 8) could be pushed upward beyond the groove $X\,X$. The proportional dividers would not allow such a motion, and therefore the generator range has to be obtained with a below the $X\,X$ line. This is done by simply considering the actual Indumor as an image of a fictitious one, $X\,X$ being the reflection line taken as a plane mirror.

Let, in Fig. 4, a point, say a', be selected on the $Y\,Y$ axis above the $X\,X$ axis, and let a complete vector diagram of currents and voltages be drawn, following exactly the method used for the point a below the $X\,X$ axis. The new diagram will give an operating condition of the machine working as a generator. Let now an image of the new diagram be drawn below the $X\,X$ axis, as if this axis were a plane mirror. Comparing this image diagram with one actually shown in Fig. 4 for the motor range, it will be found that the two differ from each other only in the direction of the vectors of primary and secondary ohmic drop, $I_1 r_1$ and $I_2 r_2$. *The vectors of ohmic drop in the generator "image" diagram are drawn in the opposite directions from those in the motor diagram.*

This relationship gives a simple method of using the Indumor for the generator range. It is only necessary to set the two protractors in Fig. 5 for a negative angle θ_1, and to turn the triangle $e\,y\,z$ (Fig. 8) about $e\,y$ so as to get a point f' to the left of f; this will give a negative slip.

A watch placed horizontally in front of a vertical mirror seems to run counter-clockwise when observed in the mirror. Similarly, a counter-clockwise vector diagram of the generator, when reversed into its image, becomes a clockwise diagram. This fact must be kept in mind in the interpretation of the results when operating the Indumor as an image of the real diagram.

IMPROVEMENT OF POWER FACTOR AND SPEED CONTROL

In Fig. 2, to the right, a separate sketch (a) shows the equivalent secondary circuit of an induction motor to which an external alternating e. m. f., E_3, has been added. It is well known that the magnitude and the phase angle of this external e. m. f. may be so chosen as either to change the speed of the motor or to improve its power factor, or both. This usually requires either an additional commutator machine or a conversion of the induction motor itself into a polyphase commutator motor.

Fig. 10 shows a corresponding adaptation of the Indumor to a polyphase machine in which an external e. m. f., E_3, has been added to the secondary circuit. The lettering is the same as on the left-hand side of Fig. 8.

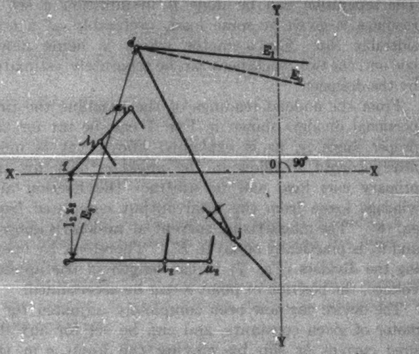

FIG. 10

The added e. m. f., E_3, is represented by the vector $e\,e'$. The extremity of the vector E_1 and of the proportional dividers for E_0 are transferred from e to e'. Otherwise the device remains the same. Electrically this means that the voltage E_0 is now balanced by the geometric sum of $I_2\,(R + r_2)$, $I_2\,x_2$, and E_3.

In Fig. 8 the primary current, I_1, lags by a considerable angle behind E_1, when the latter is turned by 90 deg. forward into its real position. In Fig. 10 the bar E_1 has been turned back sufficiently to bring the true vector E_1 almost into phase coincidence with I_1, thus raising the power factor of the machine almost to unity. By taking E_3 in the direction of the $X\,X$ axis the speed of the induction machine may be varied economically within wide limits.

The additional linkage $e\,e'$ has to be connected to the rest of the device in accordance with the nature of the external e. m. f. E_3. For example, if this e. m. f. is constant in magnitude and forms a constant phase angle with E_1, then $e\,e'$ is simply another bar rigidly connected at a certain angle to the bar E_1. This is the case in a shunt-excited polyphase commutator motor, E_1 being the voltage applied to the stator and E_2 that applied to the armature brushes. We thus obtain a new kinematic device which may be called the *Shucomor* (an abbreviation of the words "shunt commutator motor").

When a series-wound polyphase commutator motor is connected in series with the rotor windings of an induction motor, as is sometimes the case, the e. m. f., E_3, of this motor is proportional to the secondary current I_2 and the phase angle between the vectors E_3 and I_2 is constant. In this case E_3 can be represented on the Indumor in the same manner as $I_2 x_2$ or $I_1 z_1$. The secondary proportional dividers must be provided with two protractors, like the primary dividers, and $I_2 x_2$ and E_3 combined into one vector whose length is determined by the opening of the dividers which give I_2.

The author hopes to report later more in detail upon these additional possibilities of the Indumor in the study of polyphase commutator motors. As a matter of fact, he started to develop a "Shucomor," and the Indumor came out as a first attempt in this direction.

An interesting computing device has been described by Prof. R. G. Warner in an article entitled "Induction Motor Nomogram," in the A. I. E. E. JOURNAL for October 1921 (Vol. 40, p. 808). The device is based on the simple circle diagram and gives directly the numerical data for performance characteristics of three-phase 60-cycle induction motors. It is hoped that engineers interested in induction motor characteristics will investigate the relative advantages and disadvantages of the Nomogram and the Indumor, and will find out by actual experience the particular field of usefulness of each.

The development of the Indumor has been made possible through the generosity of Mr. August Heckscher of New York City, who gave to Cornell University a special fund the income from which is used for the promotion of research. To him the author's sincere gratitude is due. The device has been in a preliminary stage of development for some years previous to the grants from the Heckscher Foundation, and several of the author's students as well as the mechanicians of the College of Engineering have contributed generously of their ideas. The author wishes to express his appreciation to them all.

Discussion

Lawrence E. Widmark: We have lately been presented with two mechanical devices to replace the Behrend-Heyland Circle Diagram, one from Cornell University and the other one from Yale, and I would like to say a few words in defence of the old diagram.

We all know that the chief trouble with this diagram has been that where high precision is most desired the lowest one is obtained, depending on "that little lower left hand corner," you know, where the characteristics of the ordinary running conditions are to be found. Now, seeing the Yale device this thought suggested itself: "Have we to go to all that trouble to overcome these difficulties?" Well, at the Star Electric Motor Co. we have had in successful operation an arrangement of the diagram which I think meets requirements.

As a matter of fact, the Behrend-Heyland diagram employs a circle of *varying size* for every separate case which circle is fitted into a *fixed* coordinate system. We have reversed this procedure and are using a *fixed circle* and a *variable coordinate system*, varying with the impedance. This arrangement makes possible the "standardized diagram sheet" which I am showing here. The purpose of the larger circle is to give an enlarged view of the ordinary load conditions and the smaller one to get the maximum load and torque values in a scale just sufficient to give the desired information.

As an extra advantage of this diagram I have found interesting possibilities in respect to motor design in general which I think measure up to those promised by Prof. Karapetoff's machine. Besides this, the new diagram facilitates corrections for primary drop and saturation.

Prof. Karapetoff in his device also is able to take care of the primary drop. Neglecting saturation is, however, more questionable as I think that most of us motor designers would in a short time be out of business if we did not pay due respect to this condition.

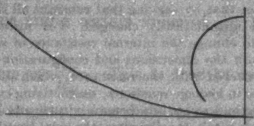

FIG. 1

H. M. Hobart: I do not think that the time-saving element in Prof. Karapetoff's device is its principal advantage. I believe that its use should lead to obtaining better designs. Many years ago designers felt that they had reached the ultimate best design, or had come pretty near to it. But succeeding years have always brought forth cheaper or better designs; usually designs which were *both* cheaper and better. This process continues, and the limit does not appear to be in sight. I believe that the progress toward the limit is slow largely because of the labor of preparing and comparing enough alternative designs to clear our minds on the subject. One who is designing an induction motor, for a certain rating works through half a dozen designs for comparison. By that time he has expended so much time and labor that he is tempted to conclude that the best design he has been enabled to arrive at by that amount of calculating must be about the right one to build. But by these new methods of Prof. Karapetoff, you can go far more extensively into the subject. You can study a much greater range of combinations and you can introduce a great many modifications and much more clearly guide your mind than when you are all tired out through laborious step by step calculations. You can much more intelligently take into account the relative influences of the many variables and limitations that are involved.

It is for these reasons that I have not the least doubt that with the introduction of these mechanical methods, the chief advantage will not be the saving in labor, but the more rapid evolution toward both cheaper and better designs. I see in the room an engineer who some six or more years ago showed me some mechanical machinery he was getting up for designing transformers, and I, at that time, was exceedingly enthusiastic for this very same reason, namely, not so much that it would save a great deal of time in calculations, but that it would lead more quickly to better and cheaper designs for a given rating. That engineer found that he did not have time enough to give to this, as it was a sort of side interest with him, but he had already at that time carried his machine to an encouraging stage of completion. I see another engineer here who, together with his colleagues has done a great amount of such work, in connection with electro-mechanical methods of calculating transmission lines.

I mention this as suggesting, perhaps, that we are at the beginning of an era of solving many complicated problems by mechanical methods, and I want again to emphasize that the most important object in these methods, in my opinion,—although it is important to save time,—is the obtaining of much better results, better economies and better characteristics of the machines.

P. Trombetta: I recognize with great respect Professor Karapetoff's very ingenious device. Unfortunately, however, it is not as easy as it might seem to change one constant of a motor without changing all the rest and this is due to the fact that the distribution of magnetism can not be restricted to any given circuit in a similar way that we can restrict the flow of electricity, and to the additional fact that the permeability of iron is not constant. Therefore, when Prof. Karapetoff states that if he wishes to change the characteristics of a motor, all that is necessary is to change the length of the particular lever which represents that particular constant which we wish to alter, he forgets the fact that by varying that constant all the rest of the constants are automatically changed. For instance, suppose it is desired to change the internal resistance of a motor, it is found that both the dimensions and configuration of the tooth and slot are altered with the resistance, which alterations give rise to changes in leakage reactance, magnetizing current, power factor, heating and so on, which may in turn make it necessary to vary the pole pitch, the diameter, the axial length of the cores and the new characteristics obtained by the indumor would therefore be meaningless.

On the other hand, in case of the calculations of line constants, in which the magnetism around the line conductor flows only through air, the permeability of which is constant, this apparatus may prove to be of great value.

V. Karapetoff: Mr. Widmark has apparently developed an improvement in the circle diagram, and I am the first one to welcome it, because I fully appreciate the wonderful usefulness of the circle diagram. I am offering a new computing device, not to supplant anything that exists, but merely something that might in some cases be also useful.

In connection with the circle diagram, I want to say that recently we have done at Cornell University something that may also add a new lease of life to this useful method, the circle diagram; namely, we have found an easy method of determining additional points on the circle diagram. In a large motor, the center of the circle lies at the same height above the axis of abscissas as the no-load loss line, but in the case of a machine with an excessive primary loss, the center of the circle lies in a different position. For such machines it is desirable to determine experimentally a third point on the circle, in addition to the no-load and the short-circuit points. We have found that it is very easy to determine the point of maximum power factor. We connect a power-factor meter in the motor circuit, and let the motor run up to speed at no-load, or else we load it until it stops. An observer follows the pointer of the power-factor meter, with a pencil, and when the pointer commences to go in the opposite direction, he leaves the pencil at that point. This gives him the maximum power factor, and a tangent to the circle. Therefore the circle can be drawn much more definitely.

I am glad that Mr. Widmark brought up the question of saturation. We have been lately working on a similar device (named the Blondelion) to imitate the performance of the synchronous machine, both the generator and the motor. In a synchronous machine it is, of course, necessary to have the saturation in the magnetic circuit properly taken into account. I am happy to say that we have solved this problem, completely so that almost any saturation curve can be imitated with that device. For highly saturated induction machines this additional linkage may be incorporated in the Indumor.

Now as to whether or not transmission lines could be treated in the same way: We have a device practically completed which imitates perfectly the performance of a long transmission line with distributed constants. We have named this device the Heavisider, after our honorary member, Oliver Heaviside. The problem is not as difficult as it may seem, and it is possible to represent kinematically the regular performance of a long transmission line without complex quantities or hyperbolic functions. The problem that interests me now is to develop a device which would represent transient phenomena on a transmission line, and not established conditions.

In conclusion I wish to point out the existence of certain useful analogies in different branches of natural science, analogies which help in the solution of certain problems. For example, take a direct-current network with known resistances and voltages, and with unknown currents. To determine the unknown currents, we have to write down and to solve a system of linear algebraic equations. Now reverse the problem,—let in a problem (which may not be an engineering problem at all, agriculture, finance, or what not) a system of simultaneous equations be given. You can connect an electrical network in which the constants of the problem will be represented by given resistances and e. m. fs., then you can insert an ammeter in each branch and read the currents. You have thus solved electrically a problem which has nothing to do with electricity.

The other day a client wanted me to solve for him a problem in mechanical oscillations. I looked at the differential equations and I saw at once that an electrical system could be built which would be expressed by similar equations. I told him that we could build for him an electric system, insert a galvanometer, follow the oscillations of the galvanometer needle, and that such a device would give him the desired information about the mode of oscillation of his entirely different mechanical system.

Skin Effect and Proximity Effect in Tubular Conductors

BY HERBERT BRISTOL DWIGHT
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The effective a-c. resistance of tubular conductors is required to be predetermined by designers, for radio installations, for large underground cables with non-magnetic cores, and for electric furnace circuits. (See Examples I to IV).

For the above purpose, sets of curves are given in this paper. The skin effect ratio for isolated tubes is shown in Fig. 1. For stranded conductors, the resistance must be multiplied also by a ratio for the spirality effect, as is approximately indicated in Fig. 2. When the return conductor is near, a ratio for the proximity effect, as indicated in Fig. 3, is also to be used. A calculation for the proximity effect ratio for thin tubes is made, and the results are compared with tests in Fig. 3.

Some of the requirements for future research work on skin effect are discussed.

The conclusion is expressed that it seems scarcely worth while providing a non-magnetic core with a 2,000,000 cir. mil, 25-cycle cable in order to reduce the skin effect, but with the other cases considered, the tubular form seems very advantageous.

THE effective resistance of tubular conductors to alternating current is desirable to know in at least three classes of work in electrical engineering: Namely in radio work, where small currents are to be carried at high frequencies; in the design of large 60-cycle single-conductor underground cables with non-magnetic cores; and in the design of electric furnace circuits where currents of the order of 30,000 or 50,000 amperes at 25 and 60 cycles are to be carried. In all of these cases, tubular conductors of convenient shape may be designed, whose effective a-c. resistance will be not much greater than their d-c. resistance, while, if the tubular form were not adopted, the a-c. resistance would be from 30 to 200 per cent, or more, greater than the d-c. resistance. The large saving of copper by this device is obvious. However, the saving does not seem worth while for 2,000,000-cir. mil, 25-cycle cables.

In this paper, curves are given by which one can estimate the a-c. resistance of tubular conductors of various kinds. The skin effect ratio for isolated tubes is shown in Fig. 1. For stranded conductors, the resistance must be multiplied by an additional ratio for the spirality effect, as is approximately indicated in Fig. 2. When the return conductor is near, a ratio for the proximity effect as indicated in Fig. 3, is also to be used. A calculation for the proximity effect in thin tubes is given, and the results are compared with tests.

It is noteworthy that the curves and formulas given in this paper are not based directly on the frequency, size of conductor or specific resistance, but only on the ratio of f to R_{dc} where f is the frequency and R_{dc} is the d-c. resistance in ohms per 1000 feet of the complete conductor. Thus, skin effect ratios measured at 100,000 cycles are applicable to large 60-cycle conductors when their proportionate shape is the same, and the proportionate shape and position of the return conductors are the same. This principle was stated by the writer in a previous A. I. E. E. paper,[1] and a mathematical proof of it was given by J. Slepian in a discussion of the same paper[1] on page 1401.

The principle may be stated as follows: A conductor, or a combination of conductors, of a certain proportionate shape and a certain value of $\frac{f}{R_{dc}}$ will have a definite value of $\frac{R_{ac}}{R_{dc}}$. This is true of isolated conductors and single-phase and polyphase circuits.

If this principle of similitude is adopted by those making skin effect tests, they will plot their test results on a base of $\frac{f}{R_{dc}}$ or $\sqrt{\frac{f}{R_{dc}}}$ instead of on a base of f as has been usually done. If the principle is adopted by designers who require to know skin effect values, they will make use of tests made on any size of conductors and at any frequency, and will correct them mathematically according to the principle of similitude, having confidence that the results so obtained will apply to their particular case.

For the particular case of proximity effect in two tubular conductors forming a return circuit (See Fig. 3) the resistance ratio depends on the ratios $\frac{f}{R_{dc}}$, $\frac{t}{d}$ and $\frac{s}{d}$. When these ratios have been determined, the proximity effect ratio is fixed.

The principle is in agreement with the various calculated formulas for skin effect and proximity effect whether for wires, tubes or straps and whether isolated or in close proximity. In fact, the principle seems almost obvious to one calculating a skin effect formula, for the first step is often to calculate the voltage drop due to resistance and reactance at any point of the cross-section of the conductor. On equating

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[1] "Skin Effect in Tubular and Flat Conductors," by H. B. Dwight, TRANS. A. I. E. E., 1918, page 1398.

this to a constant, one finds that the distribution of current over the cross-section of the conductor depends on the ratio f/R_{dc}. This is the basis of Mr. Slepian's general mathematical proof referred to above.

The writer has not seen any reliable test results of skin effect which tend to throw doubt on the above principle. In all tests published, the skin effect of round, non-magnetic isolated wires has been found to agree with the standard Bessel function formula within the limits of the errors of observation. Most experimenters have first checked up the accuracy of their measuring apparatus by making this standard test, and this seems a logical and even necessary thing to do, for skin effect ratios are admittedly difficult to measure precisely. The measurements which, judged by this standard test, appear to be made the most accurately, show the closest agreement with the principle stated above. This applies also to the effect of the spirality of stranded conductors, which is, of course, only one feature of the shape of the conductors. It may be stated that the published tests made at 60 cycles do not show the same evidence of good accuracy as tests made at higher frequencies.

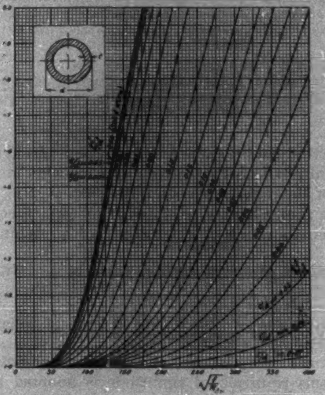

FIG. 1—SKIN EFFECT IN ISOLATED TUBES AND WIRES
R_{dc} in ohms per 1000 feet.

The curves of Fig. 1 show the skin effect in isolated tubes and wires. The skin effect in wires is well-known and a very complete and accurate table has been published by the Bureau of Standards.[2] The curves for skin effect in tubes are based on those published by the writer (see Dwight, loc. cit., Fig. 3). The curves for wires and tubes given in the present paper are plotted on $\sqrt{f/R_{dc}}$ which makes them much more useful for practical purposes. This method of plotting makes the curves independent of specific conductivity and temperature. The specific conductivity is difficult to measure precisely, as it depends on the small dimensions of the cross-section. On the other hand, the value of R_{dc}, the d-c. resistance per 1000 feet, is easy to measure precisely. The d-c. resistance of the conductor must be measured in every case in order to measure the ratio R'/R. The length of conductor whose resistance is taken is easily measured as it is several meters. This length and the d-c. resistance should always be stated when publishing skin effect tests. Thus, by plotting the curves on $\sqrt{f/R_{dc}}$, they are made of almost universal application, being applicable to copper or aluminum, high or low conductivity, high or low temperature, high or low frequency, large or small conductors and, except for spirality effect, solid or stranded conductors.

The curves are plotted on $\sqrt{f/R_{dc}}$ instead of f/R_{dc} because this makes the curves of Fig. 1 approach straight lines as asymptotes. This is indicated by the following formula, which is based on that derived by the writer, loc. cit., page 1403.

$$R'/R = \sqrt{f/R_{abs}}\sqrt{\frac{\pi\, t\,(q+r)}{r^2}}\left[1 + \frac{1}{m\, r\sqrt{2}} + \frac{3}{8\, m^2 r^2} + \frac{0}{m^3 r^3} + \ldots\right] \quad (1)$$

where $$m\, r = \sqrt{f/R_{abs}}\sqrt{\frac{8\,\pi\, r^2}{t\,(q+r)}} \quad (2)$$

where q is the inside radius of the tube, r is the outside radius and t is the thickness (See Dwight, loc. cit., page 1403) and where R_{abs} is the d-c. resistance of one cm. of the conductor in absohms. Note that $R_{abs} = 32{,}800 \times R_{dc}$ in ohms per 1000 feet. Equation (1) is applicable for large values of $\sqrt{f/R_{dc}}$ and it may be used to give approximate values of R'/R for parts of the curves beyond the range of Fig. 1. While Fig. 1 has been drawn up to cover as broad a range as possible, yet there are cases in which the value of t/d is extremely small, where it may be more convenient to use the curves of the writer's previous paper, loc. cit., Fig. 3.

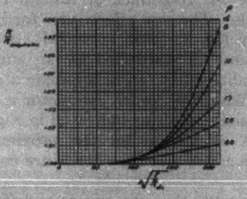

FIG. 2—SPIRALITY EFFECT RATIO IN SEVEN-WIRE CABLES
p = pitch of spirals.
d = diameter of cable.
R_{dc} in ohms per 1000 feet.

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[2] Scientific Paper No. 169 of the Bureau of Standards, by E. B. Rosa and F. W. Grover, page 226.

SPIRALITY EFFECT

As previously mentioned, the stranding of a conductor and the spiraling of the strands are features of the shape of the conductors. Therefore, a curve plotted on $\sqrt{f/R_{dc}}$ will show the effect of stranding and spiraling for a certain proportionate shape. Accurate tests have been published for seven-wire cables with both long and short pitch of spiraling[3] and the results are shown in Fig. 2. A test on a larger seven-wire cable made up to 5000 cycles[4] shows similar results. It is seen that even when the spiraling has a very short proportionate pitch, as in the case of the curve $p/d = 8$, only a small per cent is added to the a-c. resistance of an unspiraled or solid conductor of the same cross-section, for the range covered by the tests.

It has been shown by very accurate measurements (Kennelly and Affel, loc. cit., Fig. 10 and page 536) that the mere fact of dividing a conductor into parallel unspiraled strands touching one another does not increase the a-c. resistance appreciably. The increases shown in Fig. 2 are evidently due to the angle of spiraling and are approximately inversely proportional to the pitch of the spiral. From the above it appears that Fig. 2 can be used to some extent at least for approximate results with cables of more than seven wires, and with stranded conductors with non-magnetic cores, that is, with stranded, tubular conductors.

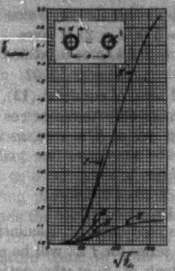

FIG. 3—PROXIMITY EFFECT RATIO IN TUBES

R_{dc} in ohms per 1000 feet.

I. $s/d = 1.0$, $t/d = 0$ (calculation).
II. $s/d = 1.008$, $t/d = 0.125$ (test).
III. $s/d = 1.5$, $t/d = 0$ (calculation).
IV. $s/d = 2.0$, $t/d = 0$ (calculation).
V. $s/d = 2.03$, $t/d = 0.125$ (test).

The increase due to spirality is only a small fraction of the usual increase due to skin effect in a solid conductor, and it is, therefore, even more difficult to measure with precision. When tests at 500 cycles show a ratio due to skin effect plus spirality effect of 1.07 to 1.1 for a seven-wire cable of 0.0457 ohm per 1000 ft.,[5] and when it is known that this cable, if unspiraled, would have a calculated skin effect ratio of 1.284, the low test value can be ascribed only to an error in measurement. The possibility that there are errors in measurement in the low-frequency tests referred to is also indicated by the fact that measurements of the same a-c. resistance sometimes differ by as much as 8 per cent (See Table IX, Middleton and Davis, loc. cit., The conclusion stated by the authors that a seven-wire cable has much less skin effect than a cable of the same size in circular mils but with a larger number of smaller wires, and, in general, that copper cables with coarse strands have less skin effect than cables with fine strands, is quite untrustworthy. It is a generalization from a single test, and that test result is in direct contradiction to the proved accurate results of references 3 and 4.

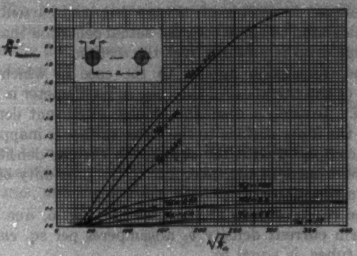

FIG. 4—PROXIMITY EFFECT RATIO IN WIRES

R_{dc} in ohms per 1000 feet.

PROXIMITY EFFECT

When conductors are comparatively close together, there is an increase in their a-c. resistance caused by the distortion of current due to their proximity. The proximity effect ratio may be defined as the ratio of the a-c. resistance when the conductors are near each other, to their a-c. resistance when they are isolated. So far as the writer is aware, only two or three tests have been published which show the proximity effect in tubular conductors. In the following paragraphs, mathematical formulas are developed for the proximity effect ratio of two extremely thin tubes forming a return circuit. The calculated results are plotted in Fig. 3, together with test results. The curves in Fig. 4, which are somewhat similar, show the proximity effect ratio in wires. From the above data, an approxi-

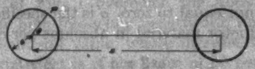

FIG. 5—CROSS-SECTION OF RETURN CIRCUIT OF THIN TUBES

mate estimate can be made of the proximity effect ratio in tubular conductors in a given case.

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[3] A. E. Kennelly and H. A. Affel, *Proceedings* of the Institute of Radio Engineers, May, 1916. Fig. 17.

[4] A. E. Kennelly, F. A. Laws and P. H. Pierce, TRANSACTIONS A. I. E. E., 1915, page 1970, Table VI.

[5] W. I. Middleton and E. W. Davis, JOURNAL of the A. I. E. E., Sept., 1921, page 760, Table VII.

As in the calculation of the formulas developed by the writer for skin effect in tubes and thin straps (Dwight, loc. cit., pages 1380 and 1392), a uniform current density over the section will first be assumed, and then successive increments of voltage drop and current will be calculated to agree with the actual condition that the voltage drop is uniform over the section.

The calculation applies to the case in which the ratio of the thickness of the tube to its diameter is very small. In such a case, the change in current density from the inner surface to the outer surface is inappreciable compared with the changes in current density in different parts of the tube, due to the proximity of the return conductor.

The reactive drop at the point P, Fig. 5, due to a uniform current density b_0 absamperes per sq. cm. in both tubes, is equal to

$$\omega\, 4\, \pi\, b_0\, a t \left[\operatorname{logh} \frac{s}{a} - \left\{ \frac{a}{s} \cos \theta + \frac{a^2}{2\, s^2} \cos 2\, \theta + \frac{a^3}{3\, s^3} \cos 3\, \theta + \ldots \right\} \right] \text{ abvolts per cm.} \qquad (3)$$

where $\omega = 2\, \pi f$ (4)

f = frequency in cycles per second (5)

and t = thickness of the tube. (6)

The reactive drop at P due to a current density $c_n \cos n\, \theta$ absamperes per sq. cm. in both tubes is

$$j\, l^2\, c_n\, \rho \left[\frac{\cos n\, \theta}{n} - \frac{a^n}{n\, s^n} \left\{ 1 + \frac{n}{\underline{|1}} \frac{a}{s} \cos \theta + \frac{n\,(n+1)}{\underline{|2}} \frac{a^2}{s^2} \cos 2\, \theta + \frac{n\,(n+1)\,(n+2)}{\underline{|3}} \frac{a^3}{s^3} \cos 3\, \theta + \ldots \right\} \right] \text{ abvolts per cm.} \qquad (7)$$

where n is not equal to zero, ρ is the specific resistivity of the conductor material in absohms per cm.^{3}, (8)

$$\text{and} \qquad l^2 = \frac{\omega\, 2\, \pi\, a\, t}{\rho} = \frac{2\, \pi f}{R} \qquad (9)$$

R being in absohms per cm. The angle θ is measured from the line joining the centers of the tubes.

Expressions (3) and (7) are derived in a manner similar to that used by H. L. Curtis[6] in calculating the proximity effect between wires for values of $\sqrt{f/R_{dc}}$ up to 140 (R_{dc} in ohms per 1000 ft.)

Assume that a current of uniform density, b_0 absamperes per sq. cm., flows in the tubes. The reactive drop at any angle θ is given by (3), and the total current is $2\, \pi\, a\, t\, b_0$ absamperes. Now assume a current of density b_1 whose resistance drop is equal and opposite to the terms in θ of (3). The reactive drop at any angle θ due to b_1 is obtained by applying equation (7) to the various terms in the expression for b_1. Numerical values of the coefficients for the Fourier series in $\cos \theta$, $\cos 2\, \theta$ etc., may be written down for a given value of s/a. Thus, when $s/d = 2$ ($d = 2\, a$), the reactive drop at angle θ due to b_1 is

$$(j\, l^2)^2\, 2\, b_0\, \rho \left[-\, 0.06350 + 0.23387 \cos \theta + 0.01152 \cos 2\, \theta + 0.00069 \cos 3\, \theta - 0.00002 \cos 4\, \theta - \ldots \right] \text{ abvolts per cm.} \qquad (10)$$

The term independent of θ in formula (10) is $(j\, l^2)^2\, 2\, b_0\, \rho\, (-\, 0.06350)$ which is obtained from the series

$$(j\, l^2)^2\, 2\, b_0\, \rho \left[-\, \frac{a^2}{s^2} - \frac{a^4}{2^2\, s^4} - \frac{a^6}{3^2\, s^6} - \frac{a^8}{4^2\, s^8} - \ldots \right] \qquad (10a)$$

This series is applicable for any value of s/a, and when $s/a = 4$ ($s/d = 2$) it gives

$$+\, l^4\, 2\, b_0\, \rho \times 0.063504$$
$$= b_0\, \rho\, l^4 \times 0.12701$$

as in the second term of equation (13).

Since b_1 contains only terms in $\cos \theta$, $\cos 2\, \theta$, etc., the total current due to b_1 is zero, as is shown by the integral

$$\int_0^{2\pi} \cos n\, \theta\, d\, \theta = 0 \qquad (11)$$

The process is continued by calculating the currents b_2, b_3 etc. The series for $I\, Z'$ will be composed of the terms independent of θ in the various expressions similar to (10).

$$\text{Now} \qquad I\, R = 2\, \pi\, a\, t\, b_0 \frac{\rho}{2\, \pi\, a\, t} = b_0\, \rho \qquad (12)$$

By dividing this into the series for $I\, Z'$, we obtain the series for

$$\frac{R' + j\, X'}{R}.$$

The real terms give a series for R'/R.

Thus, when $s/d = 2$,

$$R'/R = 1 + 0.12701\, l^4 - 0.10965\, l^8 + 0.09599\, l^{12} - 0.08435\, l^{16} + 0.0742\, l^{20} - 0.0653\, l^{24} + \ldots \qquad (13)$$

When $s/d = 1.5$

$$R'/R = 1 + 0.22872\, l^4 - 0.17337\, l^8 + 0.13619\, l^{12} - 0.10804\, l^{16} + 0.0860\, l^{20} - 0.0684\, l^{24} + \ldots \qquad (14)$$

When $s/d = 1$

$$R'/R = 1 + 0.53530\, l^4 - 0.25686\, l^8 + 0.15408\, l^{12} - 0.0961\, l^{16} + 0.0604\, l^{20} - 0.0381\, l^{24} + \ldots \qquad (15)$$

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[6] Scientific Paper No. 374 of the Bureau of Standards, Washington, D. C., 1920, by H. L. Curtis.

Now, from equation (9),

$$l = \sqrt{f/R}\,\sqrt{2}\,\pi \qquad (16)$$

when R is measured in absolute units. The principle that the value of skin effect depends on the value of f/R is self-evident for this type of circuit.

Equations (13) to (15) can be evaluated for values of l less than 1, that is, for values of $\sqrt{f/R_{dc}}$ less than about 72 (R_{dc} in ohms per 1000 ft.). Note that in this calculation the a-c. resistance when the tubes are isolated is the same as the d-c. resistance, since the tubes are assumed to be very thin.

Curves I, III and IV calculated as above for $s/d = 1, 1.5$ and 2 are plotted in Fig. 3 and are shown in comparison with test curves II and V, the data for which are given in Table VIII, of the paper by Kennelly, Laws and Pierce, loc. cit.

The curves for the proximity effect of wires (defined as R'/R_{isolated}) are not very different from those for tubes, when they are plotted on $\sqrt{f/R_{dc}}$. In Fig. 4 are plotted test curves described in Table V, Kennelly, Laws and Pierce, loc. cit., ($s/d = 1.03, 1.68, 6.5$ and 18), Table VI, Curtis, loc. cit., ($s/d = 1.06, 1.27, 2.08$ and 3.0) and a calculated curve for $s/d = 2.0$ published by J. R. Carson.[7]

These curves should be of some use in estimating the proximity effect in tubes, especially when the tubes are thick.

From the above it appears that there is opportunity for very useful measurements to be made of skin effect, spirality effect and proximity effect of tubular conductors as well as other types of conductors. The electrical engineering profession is much indebted to those who have made the tests so far published. These investigators have for the most part done their work so accurately that future tests, in order to add to our knowledge of the subject, must be made with very great precision and accuracy. Test results should not be presented as isolated results for certain sizes of conductor only, but they should be presented as general curves, applicable to all frequencies and all sizes of conductors or circuits of the specified shape. If there is any doubt in the minds of the investigators as to the propriety of doing this, they should remove such doubt by making a series of tests to check up the matter.

In this connection, it is necessary to point out that the "penetration formula" advocated by Middleton and Davis, loc. cit., is a formula which had been originally calculated and intended for very high frequencies, and it is inaccurate and liable to give rise to misleading results if used for large conductors at 60 cycles. This can be shown by plotting the results of the penetration formula alongside of the curve for solid wire in Fig. 1.

In deriving the penetration formula for solid wire, one starts with the high-frequency, asymptotic formula (1) of this paper, first making it applicable to solid wires by putting $t = r$ and $q = 0$. Next, discard all the terms of the series in the bracket except the first two, thus obtaining the equation of the straight line which is the asymptote to the curve of R'/R. This involves considerable error at low frequencies, where the curve of R'/R departs from a straight line, as is seen in Fig. 1. But there is another error, or approximation, still in the penetration formula. If R' is equal to the d-c. resistance of a tube of outer radius r and thickness t,

$$R/R' = \frac{2\,t}{r} - \frac{t^2}{r^2} \qquad (15)$$

In order to compare this with (1), the reciprocal of (1) is expanded by the binomial theorem, assuming that $m\,r$ is large, and the series is written

$$1 - \frac{1}{m\,r\,\sqrt{2}}\,.$$

The combined effect of the two approximations is found by plotting the results on Fig. 1. Besides giving actual errors for solid wires, the penetration formula as used by Middleton and Davis, loc. cit., (formula B), has the following disadvantages:

In using the constant 0.00384 for cables, it is assumed that the specific resistance of a mixture of copper and air such as the cable, is the same as the specific resistance of solid copper, but this is not the case. (This assumption is made also in Table II, Middleton and Davis, loc. cit.) By specifying the single constant 0.00384 for copper, no allowance is made for copper of low conductivity, or for changes in temperature, and these items are of considerable importance. By taking the penetration from the center line of the outside wires, an arbitrary assumption is made in order to make a few readings more consistent. The impression is given that the penetration formula can be used to determine the skin effect ratio of tubes, which is not at all correct.

The curves of Fig. 1 overcome the above disadvantages of the high-frequency penetration formula.

A 2,000,000-cir. mil cable, whose increase in resistance due to skin effect is of the order of 30 per cent at 60 cycles, is evidently worth while redesigning in order to reduce the skin effect. The increase in cost of manufacture and installation of the lead-covered cable due to the larger outside diameter when designed as a tube must be balanced against the decrease in cost due to less copper being required for the same a-c. resistance. In order to make such a comparison it is necessary to have a method of determining the skin effect in various designs of tubular conductors, and curves such as those of Fig. 1, together with curves to give a correction for spirality effect provide such a method. (See Example III.)

Care should be taken not to allow a cable carrying a heavy current to approach any magnetic material when precise measurements of the resistance loss are being taken. If the cable is near a steel beam, or possbily even a number of nails in a wooden floor on which the cable might be lying, an appreciable increase in the effective resistance could be caused.

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[7] "Wave Propagation over Parallel Wires: The Proximity Effect," by J. R. Carson, *Philosophical Magazine*, April, 1921, page 632.

It is to be hoped that further precise tests of skin effect will be made, so that the curves required in designing can be made more accurate and more complete.

EXAMPLE I

Find the a-c. resistance at 60 cycles of a non-flexible lead for a 15,000-ampere resistance furnace. With certain types of furnace which have a long, narrow shape, it is necessary to construct such a lead 40 or 50 feet long parallel to the furnace and about 6 feet away from it. The furnace is itself the return conductor, so that interlacing is impossible.

First assume a round, solid conductor with average current density 1000 amperes per sq. in., that is, with 15 sq. in. cross-section.

R_{dc} = 0.00072 ohm per 1000 feet at 100 deg. cent.

$\sqrt{f/R_{dc}} = 288$ and $\sqrt{f/R_{abs}} = 1.59$

$R'/R = 1.59 \sqrt{\pi} + 0.25 = 3.07$ by formula (1).

The proximity effect ratio is 1.03, since $s/d = 16$ (See Fig. 4).

Therefore, the a-c. resistance of the solid, round conductor is 0.0023 ohm per 1000 feet. The a-c. resistance of a bundle of cables is practically the same as that of the solid conductor. The a-c. resistance of any non-tubular form of conductor, such as a group of ventilated straps, is very much greater than the d-c. resistance and so it is worth while considering a tubular conductor, as in the following paragraph.

Assume that the conductor is a tube of 12 inches diameter, made of copper sheet 0.35 inch thick.

Section = 12.8 sq. in.

R_{dc} = 0.00084 ohm per 1000 feet at 100 deg. cent.

$t/d = 0.029$

$\sqrt{f/R_{dc}} = 267$

Therefore, $R'/R = 1.05$ from Fig. 1.

Since $s/d = 6$, the proximity effect ratio will be of the order of 1.1. (See Fig. 3).

The a-c. resistance of the tube at 60 cycles is thus about 0.0010 ohm per 1000 feet. The tubular conductor is seen to have double the a-c. conductivity of the non-tubular form, although the weight is 15 per cent less. The weight could evidently be reduced still further.

The large diameter of the tubular lead reduces the reactance and raises the power factor of the 60-cycle furnace load, which is sometimes desirable. If the heated air and the radiation from the furnace cause the lead to run too hot, the tubular shape is advantageous in that cool air from outdoors can be blown through it by a ventilating fan.

EXAMPLE II

To estimate the a-c. resistance of a flexible electric furnace lead for 30,000 amperes.

First, if the lead is composed of a bundle of bare cables tied closely together, with the average current density in the copper equal to 1000 amperes per sq. in., the value of R_{dc} for the lead will be 0.00036 ohm per 1000 feet at 100 deg. cent. This depends directly on the fact that the cross-section of the copper is 30 sq. in. At 60 cycles

$$\sqrt{f/R_{dc}} = 408 \qquad \text{and} \qquad \sqrt{f/R_{abs}} = 2.25$$

$R'/R = 2.25 \sqrt{\pi} + 0.25 = 4.25$ from formula (1).

The spirality effect ratio will be comparatively small, being of the order of 1.2. The proximity effect ratio for a three-phase circuit will not be greatly different from that for a return circuit indicated in Fig. 4. This ratio will also be small, being of the order of 1.03 if the leads are 6 feet apart, s/d being about 10.

The a-c. resistance of the lead is therefore approximately 0.0019 ohm per 1000 feet.

Second, if the lead is designed as a hollow, flexible cylinder composed of 70 cables of 400,000 cir. mils each, held apart by 20-inch circular spacers, the total section of copper is 22 sq. in. Therefore, $R_{dc} = 0.00050$ and $\sqrt{f/R_{dc}} = 346$ at 60 cycles and 100 deg. cent.

The cylinder made up of a single layer of cables is quite similar to a tube of thickness 0.72 inch or less so that $t/d = 0.034$. Therefore, from Fig. 1, $R'/R = 1.20$. The proximity effect ratio is about 1.2, as may be seen from Fig. 3, taking $s/d = 3.4$ The spirality effect ratio is of the order of 1.2 as for the more compact bundle of cables previously considered.

The a-c. resistance of the flexible tubular lead is, therefore, approximately 0.00086 ohm per 1000 feet.

It is seen therefore that the tubular lead, which has 25 per cent less weight than the non-tubular form, has over twice as much a-c. conductivity. Since the tubular lead is very well ventilated, its weight could doubtless be cut down considerably. The exact dimensions used above are for an example only to show the method of estimating the a-c. resistance.

The writer understands that this tubular form of flexible lead has been constructed and successfully used with electric furnaces and that it is sufficiently flexible for the purpose. A little calculation will show that its reactance is enough less to increase the power factor of the furnace load appreciably. An easy method such as the one here given of estimating the greatly increased conductivity of tubular leads compared with more usual designs should help make them be applied more frequently.

EXAMPLE III

To find the a-c. resistance at 60 cycles of a 2,000,000 cir. mil cable both without and with a non-conducting core.

R_{dc} = 0.0054 ohm per 1000 feet.

$\sqrt{f/R_{dc}} = 106$

$R'/R = 1.29$ for the coreless cable, from Fig. 1.

Therefore the a-c. resistance is 0.0069 ohm per 1000 feet, neglecting spirality effect.

If a 2,000,000-cir. mil tubular cable be wound on a non-conducting core 1.125 inches in diameter, the outside diameter, d, of the copper will be approximately 1.96 inches.

Therefore, $t = 0.417$ inch and $t/d = 0.213$

As above, $\sqrt{f/R_{d.c.}} = 106$

and therefore, from Fig. 1, $R'/R = 1.08$. Thus the a-c. resistance is 0.0058 ohm per 1000 feet, neglecting spirality effect.

The spirality effect ratio would be small for both the above cases since $\sqrt{f/R_{d.c.}} = 106$ (See Fig. 2).

EXAMPLE IV

To find the a-c. resistance at 25 cycles of a 2,000,000-cir. mil cable both without and with a non-conducting core.

$R_{d.c.} = 0.0054$ ohm per 1000 feet.

$\sqrt{f/R_{d.c.}} = 68$

$R'/R = 1.063$ for the coreless cable, from Fig. 1.

Diameter of copper = 1.67 inches. Assume that a return conductor is at a distance of 8 inches, center to center. Then $s/d = 4.8$ and the proximity effect ratio is about 1.010 (See Fig. 4). The spirality effect at 25 cycles is practically negligible (See Fig. 2).

Second, assume that a non-magnetic core of 0.625 inch diameter be provided, as recommended in Table XV, Middleton and Davis, loc. cit., for a 2,000,000-cir. mil cable at 25 cycles. The diameter of the copper is increased to 1.78 inches and from this

$t/d = 0.324$

Now $\sqrt{f/R_{d.c.}} = 68$ and therefore,

$R'/R = 1.035$ from Fig. 1.

As before, the spirality effect is practically negligible. The proximity effect ratio, as given by Fig. 3, is about 1.015. The slight increase in proximity effect is due to two reasons. First, the value of s/d has been decreased to 4.5 and, second, a comparison of Figs. 3 and 4 shows that the curves for tubes are slightly higher than those for wire, as would be expected from the nature of the problem.

Providing a non-magnetic core as above has therefore decreased the a-c. resistance 2.8 per cent as regards Fig. 1, increased the a-c. resistance 0.5 per cent as regards Figs. 3 and 4, and increased the diameter of the copper 6.6 per cent, thus increasing the surface for heat radiation slightly.

From these results, it does not seem to be worth while to put a non-magnetic core in a 2,000,000-cir. mil, 25-cycle cable in order to reduce the skin effect, and still less worth while in a 1,500,000-cir. mil, 25-cycle cable as recommended in Table XV, Middleton and Davis, loc. cit. The skin effect ratio of the latter cable, without a core is 1.03.

Discussion

E. W. Davis: Many learned and excellent papers have been presented before this society and other physical or technical societies, on the subject of skin effect in conductors carrying alternating currents. These papers have not, however, been interpreted for the average engineer to understand.

For radio frequencies and small sized conductors, theoretical formulas have been checked and it has been assumed that these formulas would apply to larger conductors at the lower power frequencies.

Except in the paper of Mr. W. I. Middleton's and the speaker's the data of tests conducted on actual commercial power cables at the low frequencies of 25 and 60 cycles have not been published as far as the speaker has been able to determine.

Tables furnished by manufacturers or put out by engineers of purchasing companies calling for rope cores in power cables show a remarkably wide variation in the size of cores for the same working conditions. Each table is based on some theoretical mathematical formula that is probably quite as correct as the one worked out by Mr. Dwight.

One of the simplest conceptions of skin effect and one that is quite universally used in elementary text books on electricity, is that of the depth of penetration of alternating current from the surface of a conductor. Most of us remember our high school or college instructors saying that an alternating current travels on the outside of a conductor. Alexander Gray in "Absolute Measurements in Electricity and Magnetism" gives a very interesting discussion of this conception of skin effect.

The experimental work of Mr. Middleton and the speaker in 1921 was done on commercial power cables at commercial frequencies, for the purpose of furnishing engineers with specific experimental information on the subject of skin effect in power cables. The work was done for a specific purpose, and that purpose was accomplished. The results published are quite trustworthy for the range of sizes tested and at some later date we hope to continue our tests on even larger sizes of conductors.

The constant 0.00384 used, and to which Mr. Dwight takes exception, was checked for the copper used in the actual construction of the cables.

We do not necessarily recommend the rope cores given for the smaller sizes of conductors at 25 cycles, but include them in our paper merely as an example of what these cores should be, if used.

A. S. Dana: I wish to call attention to some measurements which were made at the Massachusetts Institute of Technology in the year 1915, and which were determined to a considerable degree of accuracy under the guidance of Dr. A. E. Kennelly. The results on a 7-strand, 19- and a 37-strand are very different from those found by Middleton & Davis. The 7-strand cable, as I understand it, in the Middleton & Davis[1] paper has a much smaller skin effect than a solid conductor cable of the same cross section. The mean value measured by Davis. 1.089 at 500 cycles, but that of a solid wire of approximately the same copper cross section is 1.293, or the skin effect Mr. Davis found on a 7-strand cable was about 20 per cent less than that of the equivalent solid wire. Mr. Dwight ascribed this large difference to an error in Mr. Davis' measurements. At frequencies above 1250 cycles and 60-cm. spacing of the return conductor Mr. P. H. Pierce found the skin effect of 7-strand cable was greater than the solid. I think Mr. Pierce in a publication[2] previous to 1915 was the first to note and publish this effect. Dr. Kennelly desired me to check these measurements on 7-strand, and solid wire in 1915. I found that the skin effect of a 7-strand conductor is greater than that of the solid conductor above a certain frequency depending on the spacing of the return conductor, and the paper by Kennelly & Affel[3] at radio frequencies proved the same conclusion, and the cause was ascribed to the spirality effect. The spirality effect was later taken up in more detail and Mr. Dwight has gone still further.

I think it is generally considered that by stranding a conductor the skin effect is reduced as the number of strands is increased (providing the number of strands is greater than 7). On the 19-strand and 37-strand cables we found this to be the case: the skin effect was less than in a solid conductor of the same cross section, and also the skin effect of the 37-strand was less than the 19-strand. I have obtained permission from the Institute to publish these results from 60 to 5000 cycles since I think that they may be of value to other people interested in this problem. They appear in Figs. 1, 2, 3, 4, 5, 6. Each cable was measured in the form of a rectangle with three different spacings of the long sides. The effect of the return conductor was negligible at 60-cm. spacing.

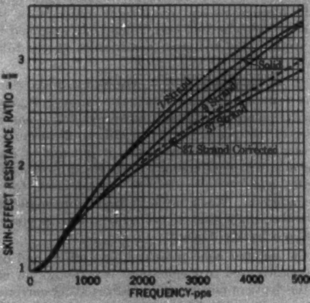

FIG. 1—EFFECT OF STRANDING ON SKIN-EFFECT

Separation approximately 60 cm., No. 0000 B & S Copper Cable. The 37-strand cable has smaller cross section than the others. Curve "37 Strand Corrected" takes this into account.

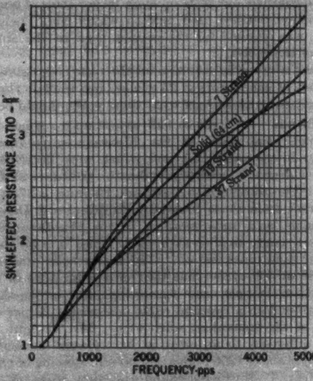

FIG. 2—EFFECT OF STRANDING ON SKIN-EFFECT

Separation approximately 2.4 cm. No. 0000 B & S Copper Cable. Temperature of Cable—Solid, 20.3 deg. cent.; 7-Strand, 15.6 deg. cent.; 19-Strand 27 deg. cent.; 37-Strand, 29 deg. cent.

Middleton & Davis, however, found just the opposite to be the case; *i. e.*, the greater the number of strands at 500 cycles the greater the skin effect. It is not safe to draw general conclusions from these measurements since at higher frequencies where more accurate results may be obtained, it is clear from the accompanying curves in Fig. 1 that the skin effect grows less as the number of strands is increased (above 7). Mr. Dwight[4] cast doubt on all the Middleton-Davis measurements and their conclusions, for the measurements of the same skin effect varied by 8 per cent. Those made by Pierce and myself were reproducible to better than 1 per cent and usually better than ½ per cent.

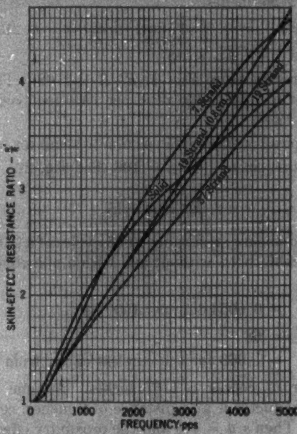

FIG. 3—EFFECT OF STRANDING ON SKIN-EFFECT

Separation approximately 0.9 cm., No. 0000 B & S Copper Cable

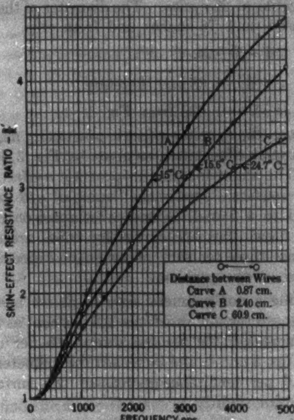

FIG. 4—SKIN EFFECT OF 7-STRAND COPPER CABLE, 211,700 CIR. MILS

Distance between wires—Curve *A*, 0.87 cm.; Curve *B*, 2.4 cm.; Curve *C*, 60.9 cm.

There is one thing more I would like to say—it may be an unfortunate choice of words, but Mr. Davis speaks of the penetration of the current as being only to a certain distance from the exterior of the conductor. This is not true, for the current goes to the center. However, it decreases at a great rate, starting from the circumference, and what is usually meant is that a tube having a thickness equal to this "penetration" of which they speak, will offer the same resistance to direct current, that the complete solid conductor offers to alternating current. Furthermore, I believe in the Middleton-Davis tests they took solid conductors, computing this depth of penetration, or the equivalent conducting layer, and decided that the material inside this ring could be thrown away and rope substituted, giving approximately the same a-c. resistance.

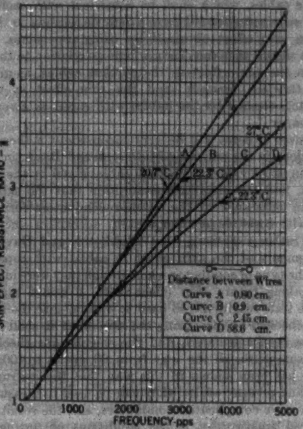

FIG. 5—SKIN EFFECT OF 19-STRAND COPPER CABLE, 210,700 CIR. MILS.

Distance between wires—Curve *A*, 0.80 cm.; Curve *B*, 0.9 cm.; Curve *C*, 2.45 cm.; Curve *D*, 58.6 cm.

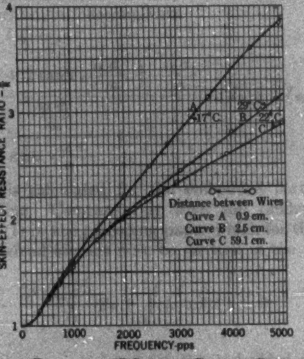

FIG. 6—SKIN EFFECT OF 37-STRAND COPPER CABLE, 198,200 CIR. MILS.

Distance between wires—Curve *A*, 0.9 cm.; Curve *B*, 2.5 cm.; Curve *C*, 59.1 cm.

You will find that this may be practically true in some cases where the diameter of the conductor and the frequency are high, but at the lower frequencies, the conductor with the center removed would have a greater resistance than the completed conductor.

For the benefit to those who care to use Gray's formula which was employed by Middleton & Davis, I think it should be pointed out that this formula is an approximation and only for use when the diameter of the conductor is so large or the frequency so high that the wire can be considered a strip of infinite width, or a tube of very small thickness. This formula does not contain any symbol for the radius of the wire, and would lead one to think that the depth of the equivalent conducting layer is independent of the radius of the wire, and varies only with the frequency and the conductivity. Using the notation which Dr. Kennelly has used in the three papers[2, 3, 5], I wish to call attention to the fact that the product of αX must be 6 or greater to use this formula with approximate accuracy. With the 2,000,000-cir. mil cable with an outside diameter of 1.625 in. in the Middleton & Davis paper at 60 cycles this product of αX is only about 3.42 instead of being greater than 6, hence that formula should not be used unless these conditions are understood, and only a rough result is desired. A formula for the equivalent skin thickness of any wire is given by Dr. Kennelly[2], page 790. In this the radius of the wire has an important part.

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H. B. Dwight: In dealing with the problem of the skin effect in a conductor of a given form of cross-section, it is necessary to try to make all the measurements which have been made with that form of section, consistent with each other. There is no doubt that they ought to be consistent, for the phenomenon of skin effect in a non-magnetic conductor at high frequency is caused by a magnetic field of the same shape as that surrounding a similar conductor in a low-frequency test.

The way in which high-frequency tests can be compared with low-frequency tests to see if they are consistent is to correct them for frequency according to the "principle of similitude," described in the third and following paragraphs of my paper.

Mr. E. W. Davis, in the second paragraph of his discussion, states that it has been "assumed" that the same laws apply to high-frequency and low-frequency tests. The principle of similitude is not an assumption. The writer gave definite reasons for it in his A. I. E. E. paper in 1918 and Mr. J. Slepian published at the same time a conclusive mathematical proof of it. (Reference 1.) If, therefore, any one should wish to cast doubt on this principle, the burden of proof is on them, and they should show evidence, either mathematical or experimental, that the principle of similitude is not true.

The question of whether the penetration formula should be used in connection with large conductors at commercial frequencies is best considered by using a direct comparison between the results of this approximate formula and the correct results, as shown in the Fig. 7. The range required for large

60-cycle cables is up to 30 per cent increase of resistance. In this range it can be seen that the penetration formula gives 37 per cent increase of resistance where it should give 30 per cent. It gives 26 per cent where it should give 20 per cent, and it gives zero per cent where it should give 3 per cent.

Such large discrepancies show that the penetration formula does not give a close approximation for the range considered. If a calculation is to be of use in deciding questions of design of large cables, it should not give errors as large as 7 per cent in a quantity which amounts to not more than 30 per cent. The same statement applies to test results having discrepancies between duplicate readings amounting to several per cent.

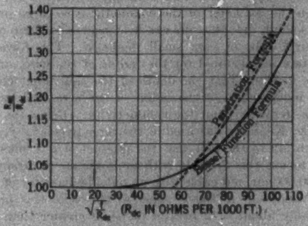

Fig. 7—Skin Effect in Solid Round Wire

The penetration formula was originally published by physicists who were discussing skin effect at high frequencies with increases in resistance of several hundred per cent. Under such conditions, the error due to the penetration formula is quite small.

If a series of rope core sizes is to be chosen for 25-cycle and 60-cycle cables, which shall be consistent with each other, the sizes of rope cores should have a definite relation to the improvement in skin effect obtained by using rope cores. The sizes of cores should therefore have a definite relation to the difference between the skin effect in the coreless cables, as given by the Bessel function formula, and the skin effect in the tubular conductors formed by the cables with cores, as given by Fig. 1 of my paper.

The sizes of cores will be very inconsistent if they are chosen as was done in the paper by Middleton and Davis, in accordance with skin effect values in coreless cables given by the penetration formula, and the incorrect assumption that the skin effect increase in resistance in the tubular conductors formed by the cables with cores, is zero per cent.

It is rather surprising that Middleton and Davis made no measurements of the skin effect in cables with rope cores, for that is the type of conductor whose design they were investigating.

In making future skin effect tests, I would suggest, since accurate tests results are so hard to obtain, that the instruments be first checked by measuring the skin effect in solid round rods. This has been calculated, and the calculations checked closely by measurements all the way from 60 cycles to 100,000 cycles. After it has been shown in this way that the instruments give correct and precise results, they can be used to measure the skin effect in more complicated conductors, and the results would be considered trustworthy if the conditions of testing the solid rods and the other conductors were substantially the same.

Heat Losses in Stranded Armature Conductors

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In the present paper, which is a continuation of one presented at the last annual convention, the author extends the method of complex hyperbolic functions to the solution of the problem of heat losses in stranded conductors embedded in rectangular slots. In the preceding paper the discussion was confined to solid conductors and to those having an infinite number of strands. In the latter case, the insulation between the strands was assumed to have no appreciable thickness. In the present paper, conductors are considered which have a finite number of strands separated by insulation of appreciable thickness. In the mathematical development which is to follow, free use is made of the results obtained in the first paper.

THE first step in the solution of the problem of heat losses in stranded armature conductors is to obtain an expression showing the relation between the currents in adjacent strands. If two strands are adjacent at any point, they are adjacent throughout their length. If the conductor is turned over in the end connection, the strand b, which is above a in one coil side, is below a in the next coil side, Fig. 1. The difference in pressure per half turn between these two strands is that between the lowest element of b and the highest element of a. If the conductor is turned over in the end connection, in the next half turn, this difference is between the lowest element of a and the highest element of b. The difference in pressure in each of these is cases given in equations (**6d**) and (**6r**). By the proper substitution, these equations can be written in terms of the currents in the adjacent strands and the current in the slot below them. See equations (**7a**) and (**7b**). These two equations are similar in form. Between the points at which the strands are joined together, the sum of all of these half-turn differences in pressure must be zero. This equation, (**8**), may be written in following form:

$$(I_{c(p+1)} - I_{c_p}) - \frac{\left(\alpha a + 2\tanh\dfrac{\alpha d}{2m}\right)\dfrac{\alpha d}{m}}{\dfrac{\dfrac{\alpha d}{m}}{\sinh\dfrac{\alpha d}{m}} + \dfrac{l_2}{l_1}}\left(I_0 + \sum_1^p I_{c_p}\right) = 0;$$

where α is calculated for the embedded portion of the winding. Compare this with the fundamental equation (1) in the preceding paper which for the case of infinitesimal strands may be written in the following form:

$$w\,dx\,d\text{ç} - \frac{\alpha^2\,(dx)^2}{1 + \dfrac{l_2}{l_1}}\left(I_0 + \int_0^x w\,\text{ç}\,d\,x\right) = 0;$$

where α is also calculated for the embedded portion of the winding only, and l_1 and l_2 are respectively the length of the armature core and the length of an end turn. Notice that these equations are similar. The first term in each is the vector difference between the currents in adjacent strands. The coefficients of the second terms are the same when the number of strands, m, increases without limit and there is no insulating space, a, between them. It is further shown that the vector constants, I_0, are identical in the two equations. This similarity suggests that the currents in the strands of the stranded conductor may be equal to those in corresponding divisions of a solid conductor of the same depth. In the latter case, the imaginary strands would of course not be separated. (Fig. 2.)

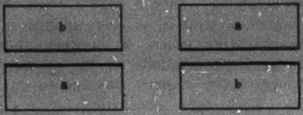

FIG. 1

Such proves to be the case provided the hyperbolic angular depth, $\beta\,d$, of the solid conductor has a certain value. This value is determined by the relation (Equation **10a**):

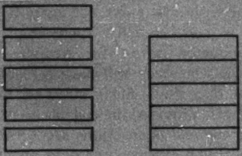

FIG. 2

$$\sinh^2\frac{\beta d}{2m} = \frac{\dfrac{\alpha d}{2m}\left(\dfrac{\alpha a}{2} + \tanh\dfrac{\alpha d}{2m}\right)}{\dfrac{\dfrac{\alpha d}{m}}{\sinh\dfrac{\alpha d}{m}} + \dfrac{l_2}{l_1}}$$

Were it not for this relation between the currents in the two cases the completion of the solution would be much more difficult. The reason is that the current

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up to any strand in the stranded conductor must be determined by a summation of vector quantities whereas in a solid conductor the current up to any point may be obtained by integration, a much simpler process. The current in any strand may also be obtained by integration between the proper limits.

This equality of the currents in a stranded conductor and a solid one recalls the equality of currents and of voltages that exists in an artificial transmission line and a smooth line when there is a certain relation between their constants.

We are now in a position to determine the expressions for the resistance drop in either the top or bottom strand of a conductor. It is only in the case of strands of infinitesimal thickness that the expressions are the same. Compare equations (**13b**) and (**14b**) with equation (**7**) in the preceding paper. They are identical except that M and N in the preceding paper are replaced by similar functions, M' and N' and that there are terms involving T' and S' which would disappear if the number of strands, m, were infinite and there were no insulating space, a, between them. We must also derive expressions for the pressure acting in conductors below a given one due to flux within the latter. These expressions are given in equations (**15b**) and (**16b**). These expressions are identical with the corresponding ones for solid or finely laminated conductors except that N' replaces N, that T' replaces $\alpha^2 d^2$ to which it reduces if there are an infinite number of laminations with no space between them, and that there is an added term involving S', a pure imaginary, which depends upon the insulating space between the laminations.

Having determined these four pressure equations, the determination of the heating loss or of the leakage impedance follows precisely the same procedure that was used in the preceding paper.

The author wishes to point out again a fact which he believes is not generally appreciated. A finely stranded conductor with the strands continuous throughout the whole coil will have a resistance ratio equal to that of a single finely stranded half turn of one half its depth, provided the coil has an even number of turns and the end connections are turned over on *one side only*. For conductors up to about one inch in depth, the alternating-current resistance is then but 1 or 2 per cent greater than the direct-current resistance.

Mathematical Analysis

The description of windings considered follows. The embedded portions of the winding are in open reactangular slots; there are two coil sides per slot; the pitch is either full or fractional; each coil side has n layers or conductors, and each layer has m laminations or strands; the strands occupy the same relative positions throughout the embedded portion of any half turn; the strands are arranged one above the other and have equal rectangular cross-sections; the strands are separated by insulation of uniform thickness; when the conductors are turned over or twisted in the end connections it is done in such a manner that any strand occupies the same relative position with respect to the bottom of the conductor of which it is a part that it does with respect to the top of the successive half turn; the coil as a whole is not turned over in the end connection; strands of any conductor may be joined at the beginning and end of a half turn, a full turn, or of a complete coil; the end connections may be turned over on neither side, on one side, or on both sides.

The strands are designated by the subscripts $q\,p$. The $q\,p$ strand is the p strand of the q conductor. The number of the strand may be counted from the bottom of the conductor of which it is a part, in which case the order of the strands is said to be direct, or from the top of the conductor of which it is a part, in which case the order of the strands is said to be reverse. Thus in a winding whose strands are continuous throughout a whole coil and whose end connnections are turned over on both sides the strands are in the direct order in one coil side and in the reverse order in the other coil side of the same coil. The number of the conductor is always counted from the bottom of the coil side of which it is a part.

The armature currents are assumed to be balanced. In the end connections the r. m. s. current density throughout any strand is assumed to be constant. In the embedded portion of the coil the r. m. s. current density in any strand is variable. This vector r. m. s. current density in the embedded portion of the $q\,p$ strand is:

$$\text{ç}_{qp} = \frac{m}{w\,d}\left(I_{qp}\,\frac{\alpha\,d}{m}\,\frac{\cosh \alpha\,x}{\sinh \frac{\alpha\,d}{m}} \right.$$

$$- I_{bqp}\,\frac{\alpha\,d}{m} \tanh \frac{\alpha\,d}{2m} \cosh \alpha\,x$$

$$\left. + I_{bqp}\,\frac{\alpha\,d}{m} \sinh \alpha\,x \right) \qquad (1)$$ [1]

ç is the vector r. m. s. current density at points x centimeters from the bottom of the $p\,q$ strand; d is the net depth[2] of the conductor; d/m is the depth of one strand; w is the width of the conductor or strand; I_{qp} is the current in the $q\,p$ strand; I_{bqp} is *all* of the current in the slot *below* the $q\,p$ strand;

$$\alpha^2 = j\,\frac{8\,\pi^2\,w\,f}{\rho\,s};$$

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[1] See: Heat Losses in the Conductors of Alternating-Current Machines presented at Annual Convention A. I. E. E., June 1921. (Equation (4). For solid conductors like the $q\,p$ strand I_o is all of the current in the slot below the conductor considered.)

[2] The net depth of the conductor is the depth it would have if the insulation between the strands were of zero thickness.

where f is the frequency, w, the width of the conductor, and s, that of the slot, and ρ is the resistivity of the material of the conductor at the working temperature. ρ is assumed the same for every strand.

The current densities at the bottom, center and top of the $q\,p$ strand are respectively $c_{q_{pb}}$, $c_{q_{pc}}$ and $c_{q_{pt}}$. Substitution in equation (1) shows that

Since $x = O$,

$$c_{q_{pb}} = \frac{m}{w\,d}\left(I_{q_p}\frac{\frac{\alpha\,d}{m}}{\sinh\frac{\alpha\,d}{m}} - I_{bq_p}\frac{\alpha\,d}{m}\tanh\frac{\alpha\,d}{2\,m}\right) \quad (2)$$

$$\text{Since } x = \frac{d}{2\,m},\ c_{q_{pc}} = \frac{m}{w\,d}\,I_{q_p}\frac{\frac{\alpha\,d}{2\,m}}{\sinh\frac{\alpha\,d}{2\,m}} \quad (3)$$

$$\text{Since } x = \frac{d}{m},\ c_{q_{pt}} = \frac{m}{w\,d}\left(I_{q_p}\frac{\alpha\,d}{m}\coth\frac{\alpha\,d}{m} + I_{bq_p}\frac{\alpha\,d}{m}\tanh\frac{\alpha\,d}{2\,m}\right) \quad (4)$$

$$\text{or} \quad c_{q_{pt}} = \frac{m}{w\,d}\left\{I_{q_p}\frac{\frac{\alpha\,d}{m}}{\sinh\frac{\alpha\,d}{m}} + I_{bq(p+1)}\frac{\alpha\,d}{m}\tanh\frac{\alpha\,d}{2\,m}\right\} \quad (4a)$$

It is shown in the paper already referred to that the flux, ϕ_{q_p}, within the embedded portion of any solid conductor, the $_{q_p}$ strand for example, due to current within the conductor, I_{q_p} or example, and to all of the current in the slot below it, which in this case is I_{bq_p}, is

$$\phi_{q_p} = \frac{1}{j\,\omega}\,\frac{l_1\,\rho\,m}{w\,d}\left(I_{q_p} + 2I_{bq_p}\right)\frac{\alpha\,d}{m}\tanh\frac{\alpha\,d}{2\,m} \quad (5)$$

where l_1 is the length of the armature core. The flux, ϕ_a, between the $q\,(p+1)$ and the $q\,p$ strands is

$$\frac{4\,\pi\,l_1\,a}{s}\,I_{bq\,(p+1)},$$

which may be written in a form similar to equation (5). a is the thickness of the insulation between the strands

$$\phi_a = \frac{1}{j\,\omega}\,\frac{l_1\,\rho\,m}{w\,d}\left(I_{q_p} + I_{bq_p}\right)\frac{\alpha\,d}{m}\cdot\alpha\,a \quad (5a)$$

The proper combination of these five equations, *viz.*, (2), (3), (4), (5) and (5a) will give the heat loss in any of the types of stranded conductors we are considering. The leakage reactance due to flux within the embedded portion of the conductor may also be found.

RELATION BETWEEN THE CURRENTS IN ADJACENT STRANDS OF THE SAME CONDUCTOR

For strands numbered in the direct order, the difference in pressure between adjacent elements of adjacent strands is the difference in pressure between that in the topmost element of the p strand and the bottom element of the $(p+1)$ strand of the same conductor. For strands numbered in the reverse order this same difference is that between the pressures in the lowest element of the p strand and in the topmost element of the $(p+1)$ strand. The total difference in pressure between these adjacent elements must be zero between the points at which the strands are joined.

For strands numbered in the direct order this difference in pressure, D_d, for a half turn is

$$D_d = \left(l_1\,\rho\,c_{q\,(p+1)\,b} + l_2\,\frac{\rho\,m}{w\,d}\,I_{q\,(p+1)}\right) - \left(l_1\,\rho\,c_{q_{pt}} + l_2\,\rho\,\frac{m}{w\,d}\,I_{q_p} + l_1\,\frac{\rho\,m}{w\,d}\,I_{bq\,(p+1)}\,\frac{\alpha\,d}{m}\cdot\alpha\,a\right) \quad (6d)$$

l_1 and l_2 are respectively the lengths of the armature core and of the end connections for a half turn. The second term in each parenthesis is the resistance drop in the end connections. The third term in the second parenthesis is the drop in pressure in the $q\,p$ strand due to the flux ϕ_a. The reactance drop in the end connections due to internal leakage flux is neglected, *i. e.*, the current density is assumed to be uniform in each strand of the end connections.

Substitute equations (2) and (4) in equation (6d)

$$D_d = \frac{m}{w\,d}\,\rho\left\{\left[l_1\,I_{q\,(p+1)}\frac{\frac{\alpha\,d}{m}}{\sinh\frac{\alpha\,d}{m}} - l_1\,I_{bq\,(p+1)}\frac{\alpha\,d}{m}\left(\alpha\,a + \tanh\frac{\alpha\,d}{2\,m}\right) + l_2\,I_{q\,(p+1)}\right] - \left[l_1\,I_{q_p}\frac{\alpha\,d}{m}\coth\frac{\alpha\,d}{m} + l_1\,I_{bq_p}\frac{\alpha\,d}{m}\tanh\frac{\alpha\,d}{2\,m} + l_2\,I_{q_p}\right]\right\}$$

but $\quad I_{bq_p} = I_{bq\,(p+1)} - I_{q_p}$

Thus:

$$D_d = \frac{m}{w\,d}\,\rho\left\{\left(l_1\frac{\frac{\alpha\,d}{m}}{\sinh\frac{\alpha\,d}{m}} + l_2\right)\left(I_{q\,(p+1)} - I_{q_p}\right) - l_1\,I_{bq\,(p+1)}\frac{\alpha\,d}{m}\left(\alpha\,a + 2\tanh\frac{\alpha\,d}{2\,m}\right)\right\} \quad (6a)$$

For strands numbered in the reverse order the pressure difference, D_r, for a half turn is:

$$D_r = \left(l_1\,\rho\,c_{q\,(p+1)\,t} + l_2\,\rho\,\frac{m}{w\,d}\,I_{q\,(p+1)}\right.$$

$$+ l_1 \rho \frac{m}{w\,d}\, I_{bq_p} \frac{\alpha\,d}{m} \cdot \alpha\,a \Big)$$

$$- \left(l_1 \rho\, c_{q_p b} + l_2 \rho \frac{m}{w\,d} I_{q_p} \right) \qquad \textbf{(6r)}$$

Substitute as before

$$D_r = \frac{m}{w\,d}\,\rho \left\{ \left[l_1 I_{q\,(p+1)} \frac{\alpha\,d}{m} \coth \frac{\alpha\,d}{m} + l_1 I_{bq\,(p+1)} \frac{\alpha\,d}{m} \tanh \frac{\alpha\,d}{2\,m} + l_2 I_{q\,(p+1)} \right] - \left[l_1 I_{q_p} \frac{\frac{\alpha\,d}{m}}{\sinh \frac{\alpha\,d}{m}} - l_1 I_{bq_p} \frac{\alpha\,d}{m} \left(\alpha\,a + \tanh \frac{\alpha\,d}{2\,m} \right) + l_2 I_{q_p} \right] \right\}$$

Now $\qquad I_{bq_p} = I_{bq\,(p+1)} + I_{q\,(p+1)}$

Thus:

$$D_r = \frac{m}{w\,d}\,\rho \left\{ \left(l_1 \frac{\frac{\alpha\,d}{m}}{\sinh \frac{\alpha\,d}{m}} + l_2 \right) \left(I_{q\,(p+1)} - I_{q_p} \right) + l_1 I_{bq_p} \frac{\alpha\,d}{m} \left(\alpha\,a + 2 \tanh \frac{\alpha\,d}{2\,m} \right) \right\} \qquad \textbf{(6b)}$$

In equation **(6a)** $\qquad I_{bq\,(p+1)} = I_{bq1} + \sum_1^p I_{q_p}$;

where the first part is the current in the slot below the q conductor and the second part is the current in the q conductor below its $(p + 1)$ strand. In equation **(6b)** $I_{bq_p} = I_{bq_m} + I_q - \sum_1^p I_{q_p}$ where the first part is the current in the slot below the q conductor, the second part is the current in the q conductor and the third part, as before, is the current in the q conductor from the first strand to the p strand inclusive.

With these substitutions, equations **(6a)** and **(6b)** become

$$D_a = \frac{m\,\rho}{w\,d} \left\{ \left(l_1 \frac{\frac{\alpha\,d}{m}}{\sinh \frac{\alpha\,d}{m}} + l_2 \right) \left(I_{q\,(p+1)} - I_{q_p} \right) - l_1 \frac{\alpha\,d}{2\,m} \left(\alpha\,a + 2 \tanh \frac{\alpha\,d}{2\,m} \right) I_{bq1} - l_1 \frac{\alpha\,d}{m} \left(\alpha\,a + 2 \tanh \frac{\alpha\,d}{2\,m} \right) \sum_1^p I_{q_p} \right. \qquad \textbf{(7a)}$$

$$D_r = \frac{m\,\rho}{w\,d} \left\{ \left(l_1 \frac{\frac{\alpha\,d}{m}}{\sinh \frac{\alpha\,d}{m}} + l_2 \right) \left(I_{q\,(p+1)} - I_{q_p} \right) + l_1 \frac{\alpha\,d}{m} \left(\alpha\,a + 2 \tanh \frac{\alpha\,d}{2\,m} \right) \left(I_{bq_m} + I_q \right) - l_1 \frac{\alpha\,d}{m} \left(\alpha\,a + 2 \tanh \frac{\alpha\,d}{2\,m} \right) \sum_1^p I_{q_p} \right\} \qquad \textbf{(7b)}$$

Between the points at which the strands are joined together the sum of all of these differences in pressure in adjacent half-turn elements, *viz.*, $\Sigma\,(D_a + D_r)$, must be zero. In general this sum may be written in the form

$$\left(\frac{\frac{\alpha\,d}{m}}{\sinh \frac{\alpha\,d}{m}} + \frac{l_2}{l_1} \right) \left(I_{q\,(p+1)} - I_{q_p} \right) - \frac{\alpha\,d}{m} \left(\alpha\,a + 2 \tanh \frac{\alpha\,d}{2\,m} \right) I_0 - \frac{\alpha\,d}{m} \left(\alpha\,a + 2 \tanh \frac{\alpha\,d}{2\,m} \right) \sum_1^p I_{q_p} = 0 \qquad \textbf{(8)}$$

where I_0 is the sum of the I_{bq1}'s and the $(- I_{bq_m} - I_q)$'s divided by $2\,n$, that is in general

$$I_0 = \frac{1}{2\,n} \left(I_{bq1} - I_{bq_m} - I_q \right)$$

We will now calculate the values of I_0 for the cases that we wish to consider.

Case 1. *Strands joined at the beginning and end of each half turn.* For the q conductor of the upper coil side

$$I_0 = (q - 1)\,I + n\,I \underline{/\theta}$$

The first part of I_0 is the current in the upper coil side below the q conductor and the second part is the current in the lower coil side which in general differs in phase by an angle θ. There are n conductors in each coil side. The current in each conductor is I amperes ($I_q = I$).

Case 2. *Strands joined at the beginning and end of a whole turn but not turned over in the end connection.* For the q conductor of the coil:

$$I_0 = 1/2 \{ (q - 1)\,I + n\,I \underline{/\theta} + (q - 1)\,I \}$$
$$= (q - 1)\,I + n/2\,I \underline{/\theta}$$

Case 3. *Strands joined at the beginning and end of a whole turn and turned over in the end connection.* For the q conductor:

$$I_0 = 1/2 \{ (q - 1)\,I + n\,I \underline{/\theta} - (q - 1)\,I - I \}$$

$$I_0 = - I/2 + \frac{n\,I \underline{/\theta}}{2}$$

Case 4. *Strands joined at the beginning and end of a whole coil of n turns. End connection not turned over on either side.*

$$I_0 = \frac{1}{2\,n} \sum_1^n \left[(q - 1)\,I + n\,I \underline{/\theta} + (q - 1)\,I) \right]$$

$$= \frac{n - 1}{2}\,I + n/2\,I \underline{/\theta}$$

Case 5. *Strands joined at the beginning and end of a whole coil of n turns. End connections turned over on one side only.* The order of the strands in the first, or lowest, conductor of the upper coil side is direct, that of the next half turn is reverse. The strands in the second conductor of the upper coil side are in the reverse order while those in the next half turn are in the direct order.

In general

$$I_0 = \frac{1}{2n}\Big\{ (n\angle\theta - 1) + (-n\angle\theta - 1 - 1 + 1) + (n\angle\theta + 2 - 2 - 1) + (-n\angle\theta - 3 - 1 + 3) + \text{etc.} \Big\} I$$

$$I_0 = \frac{1}{2n}\Big\{ (n\angle\theta - 1) + (-n\angle\theta - 1) + (n\angle\theta - 1) + (-n\angle\theta - 1)\ \text{etc.} \Big\} I$$

(a) n an even number

$I_0 = -I/2$

(b) n an odd number

$I_0 = -I/2 + I/2\angle\theta$

Case 6. Strands joined at the beginning and end of a whole coil of n turns. End connections turned over on both sides. In the upper coil side the strands are all in the direct order while in the lower coil side they are all in the reverse order.

$$I_0 = \frac{1}{2n}\sum_{1}^{n}\left(n\angle\theta + (q-1) - (q-1) - 1\right) I$$

$$= -I/2 + \frac{nI\angle\theta}{2}$$

Consider a solid conductor of the same width, w, and same net depth, d, but which has an angle β instead of α. The current density in this conductor is

$$c = A'\cosh\beta x + B'\sinh\beta x$$

Imagine that this solid conductor is divided into m equal parts, *i. e.*, strands, in the same manner that the actual conductor is divided. The difference between the currents in the $(p+1)$ and p strands is

$$I'_{p+1} - I_p' = \frac{wd}{m}\,\frac{\sinh\dfrac{\beta d}{2m}}{\dfrac{\beta d}{2m}}\left(c'_{(p+1)c} - c_{pc}'\right)$$

(See equation 2)

But
$$c'_{(p+1)c} - c'_{pc} = \left(A'\cosh\frac{p+1/2}{m}\beta d + B'\sinh\frac{p+1/2}{m}\beta d\right) - \left(A'\cosh\frac{p-1/2}{m}\beta d + B'\sinh\frac{p-1/2}{m}\beta d\right)$$

Expand in terms of $p/m\ \beta d$ and $\dfrac{\beta d}{2m}$ giving

$$c'_{(p+1)c} - c'_{pc} = (A'\sinh p/m\ \beta d + B'\cosh p/m\ \beta d)\, 2\sinh\frac{\beta d}{2m}$$

Thus:

$$I'_{p+1} - I'_p = \frac{wd}{m}\,\frac{2\sinh^2\dfrac{\beta d}{2m}}{\dfrac{\beta d}{2m}}(A'\sinh p/m\ \beta d + B'\cosh p/m\ \beta d)$$

The current in this conductor up to and including the p part is

$$\sum_{1}^{p} I'_p = \int_0^{\frac{p}{m}d} w\,c'\,dx = w/\beta\,(A'\sinh p/m\ \beta d + B'\cosh p/m\ \beta d) - w/\beta\, B'$$

We will now show that these values of current can be made to satisfy the relation that has been established between the currents in adjacent strands of the actual conductor. Substitute these values of $(I'_{p+1} - I'_p)$ and $\sum\limits_1^p I_p'$ in equation (8). That is assume that the currents in the imaginary strands of the solid conductor are exactly equal to the currents in the corresponding strands of the actual conductor

$$\left(\frac{\dfrac{\alpha d}{m}}{\sinh\dfrac{\alpha d}{m}} + \frac{l_2}{l_1}\right)\frac{wd}{m}\,\frac{2\sinh^2\dfrac{\beta d}{2m}}{\dfrac{\beta d}{2m}}(A'\sinh p/m\ \beta d + B'\cosh p/m\ \beta d) - \frac{\alpha d}{m}\left(\alpha a + 2\tanh\frac{\alpha d}{2m}\right)I_0 - \frac{\alpha d}{m}\left(\alpha a + 2\tanh\frac{\alpha d}{2m}\right) w/\beta\left(A'\sinh p/m\,\beta d + B'\cosh p/m\,\beta d - B'\right) = 0 \qquad (8a)$$

This equation (8a) is satisfied if:

$$\left(\frac{\dfrac{\alpha d}{m}}{\sinh\dfrac{\alpha d}{m}} + \frac{l_2}{l_1}\right)\frac{wd}{m}\,\frac{2\sinh^2\dfrac{\beta d}{2m}}{\dfrac{\beta d}{2m}} - \frac{\alpha d}{m}\left(\alpha a + 2\tanh\frac{\alpha d}{2m}\right)w/\beta = 0 \qquad (9a)$$

and:

$$-\frac{\alpha d}{m}\left(\alpha a + 2\tanh\frac{\alpha d}{2m}\right)I_0 + \frac{\alpha d}{m}\left(\alpha a + 2\tanh\frac{\alpha d}{2m}\right)w/\beta\, B' = 0 \qquad (9b)$$

These conditions readily reduce to

$$\sinh^2 \frac{\beta d}{2m} = \frac{\frac{\alpha d}{2m}\left(\frac{\alpha a}{2} + \tanh\frac{\alpha d}{2m}\right)}{\frac{\frac{\alpha d}{m}}{\sinh\frac{\alpha d}{m}} + \frac{l_2}{l_1}} \qquad (10a)$$

and $$B' = \beta/w\, I_0 \qquad (10b)$$

If the total current in the conductor, actual or equivalent, is I, the vector constant A' is determined as in the preceding paper.

$$A' = \beta/w\left(\frac{I}{\sinh \beta d} - I_0 \tanh\frac{\beta d}{2}\right) \qquad (10c)$$

By equation (3) the current in the p strand is

$$I_p = \frac{w\,d}{m}\,\frac{\sinh\frac{\beta d}{2m}}{\frac{\beta d}{2m}}\,c_{p\,c}$$

$$= \frac{w\,d}{m}\,\frac{\sinh\frac{\beta d}{2m}}{\frac{\beta d}{2m}}$$

$$\left(A' \cosh\frac{p-1/2}{m}\,\beta d + B' \sinh\frac{p-1/2}{m}\,\beta d\right)$$

$$= 2\sinh\frac{\beta d}{2m}\left(I\,\frac{\cosh\frac{p-1/2}{m}\,\beta d}{\sinh\beta d} - I_0\tanh\frac{\beta d}{2}\cosh\frac{p-1/2}{m}\,\beta d + I_0\sinh\frac{p-1/2}{m}\,\beta d\right) \qquad (11)$$

The current in the conductor below the p strand is

$$\sum_1^{p-1} I_p = \int_0^{\frac{p-1}{m}d} w\,c'\,d\,x$$

$$= w/\beta\left(A' \sinh\frac{p-1}{m}\,\beta d + B'\cosh\frac{p-1}{m}\,\beta d - B_1\right)$$

$$= \frac{\sinh\frac{p-1}{m}\,\beta d}{\sinh\beta d} - I_0\tanh\frac{\beta d}{2}\sinh\frac{p-1}{m}\,\beta d + I_0\cosh\frac{p-1}{m}\,\beta d - I_0 \qquad (12)$$

The total current below the $q\,p$ strand of the actual conductor is

$$I_{bq} + \sum_1^{p-1} I_{qp},$$

where I_{bq} is the current in the slot below the q conductor.

If the current in any conductor and all of that below it in the slot are given the copper loss in the conductor may be calculated as described in the preceding paper. We are thus able to calculate the copper loss in any strand of any conductor. This method of calculation is far too laborious and we shall content ourselves with calculating the loss for a half turn (Case 1), a single turn (Cases 2 and 3) or for a single coil (Cases 4, 5 and 6). To do this it is necessary to obtain expressions for the voltage drop per half turn in the top element[3] of the top strand, in the bottom element[3] of the bottom strand and the voltage drop due to flux within a single conductor in all conductors below it.

The voltage drop per half turn in the topmost element of the $q\,p$ strand due to resistance and leakage below the $q\,(p+1)$ element is,

$$l_1\,\rho\,c_{q_p t} + l_2\,\rho\,\frac{m}{w\,d}\,I_{q_p} + l_1\,\rho\,\frac{m}{w\,d}\,I_{bq\,(p+1)}\,\frac{\alpha d}{m}\,\alpha\,a$$

The third term in this expression is the voltage drop due to flux within the insulation—of thickness a—that is immediately above the $q\,p$ strand. It is necessary to include this term in order that the voltage expressions about to be derived will be similar in certain respects to the general equation (8) for the currents in the strands.

By equation (4a) this reduces to

$$\rho\,\frac{m}{w\,d}\left\{\left(l_1\,\frac{\frac{\alpha d}{m}}{\sinh\frac{\alpha d}{m}} + l_2\right) I_{q_p} + l_1\,I_{bq\,(p+1)}\,\frac{\alpha d}{m}\left(\alpha\,a + \tanh\frac{\alpha d}{2m}\right)\right\}$$

The voltage drop per half turn in the topmost element of the top strand of the q conductor of the upper coil side due to resistance and leakage flux below this element is,

$$\text{drop} = \rho\,\frac{m}{w\,d}\,l_1\left[\left(\frac{\frac{\alpha d}{m}}{\sinh\frac{\alpha d}{m}} + \frac{l_2}{l_1}\right) I_{q_m} + (I_{bq_1} + I)\,\frac{\alpha d}{m}\left(\alpha\,a + \tanh\frac{\alpha d}{2m}\right)\right] \qquad (13)$$

This pressure is used when the strands are numbered in the direct order. The loss in pressure per half turn in the lowest element of the bottom strand of the $q\,p$ conductor due to resistance and leakage flux below this element is:

$$l_1\,\rho\,c_{q_p b} + l_2\,\rho\,\frac{m}{w\,d}\,I_{q_p}$$

---

[3] Due to resistance and flux below it.

By equation (2) this reduces to:

$$\text{drop} = \rho \frac{m}{w\,d}\, l_1 \left\{ \left(\frac{\frac{\alpha d}{m}}{\sinh \frac{\alpha d}{m}} + \frac{l_2}{l_1} \right) I_{q_p} - I_{b\,q_p} \frac{\alpha d}{m} \tanh \frac{\alpha d}{2\,m} \right\}$$

The loss in pressure per half turn in the lowest element of the bottom—*i. e.* the q_1—strand of the q conductor of the upper coil side due to resistance and leakage flux below this element is,

$$\text{drop} = \rho \frac{m}{w\,d}\, l_1 \left\{ \left(\frac{\frac{\alpha d}{m}}{\sinh \frac{\alpha d}{m}} + \frac{l_2}{l_1} \right) I_{q1} - I_{b\,q1} \frac{\alpha d}{m} \left(\alpha a + \tanh \frac{\alpha d}{2\,m} \right) + I_{b\,q1} \frac{\alpha d}{m} \cdot \alpha a \right\} \tag{14}$$

This pressure is used when the strands are numbered in the reverse order. The equation is written in this form so that it will be similar to equation (13). When the strands are continuous from one half turn to the next and the end connection is turned over between successive half turns the top strand of one half turn becomes the bottom strand of the next half turn. Thus in equations (13) and (14) the I_{q_m} is the same as I_{q1}.

The flux in the q conductor is,

$$\phi_q = \sum_1^m (\phi_{q_p} + \phi_a)$$

By equations (5) and (5a) this is,

$$\phi_q = \frac{1}{j\,\omega}\, l_1 \rho \frac{m}{w\,d} \frac{\alpha d}{m} \left\{ \tanh \frac{\alpha d}{2\,m} \sum_1^m (I_{q_p} + 2\, I_{b\,q_p}) + \alpha a \sum_1^m (I_{q_p} + I_{b\,q_p}) \right\}$$

$$= \frac{1}{j\,\omega}\, \rho \frac{m}{w\,d}\, l_1 \left\{ I\, \frac{\alpha d}{m} \left(\alpha a + \tanh \frac{\alpha d}{2\,m} \right) + \sum_1^m I_{b\,q_p} \frac{\alpha d}{m} \left(\alpha a + 2 \tanh \frac{\alpha d}{2\,m} \right) \right\}$$

The summation in the second term in this expression for the flux may be written,

$$\begin{aligned} \sum_1^m I_{b\,q_p} = \Big(& I_{b\,q1} + 0 \\ & + I_{b\,q1} + I_{q1} \\ & + I_{b\,q1} + I_{q1} + I_{q2} \\ & + I_{b\,q1} + I_{q1} + I_{q2} + I_{q3} \\ & \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ & + I_{b\,q1} + \sum_1^{p-1} I_{q_p} \\ & \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \quad \cdot \\ & + I_{b\,q1} + \sum_1^{m-1} I_{q_p} \\ = & \; m\, I_{b\,q1} + \sum_1^{m-1} \sum_1^{p-1} I_{q_p} \Big) \end{aligned}$$

From equation (8) we have,

$$\frac{\alpha d}{m} \left(\alpha a + 2 \tanh \frac{\alpha d}{2\,m} \right) \sum_1^{p-1} I_{q_p} = \left(\frac{\frac{\alpha d}{m}}{\sinh \frac{\alpha d}{m}} + \frac{l_2}{l_1} \right) (I_{q_p} - I_{q\,(p-1)}) - \frac{\alpha d}{m} \left(\alpha a + 2 \tanh \frac{\alpha d}{2\,m} \right) I_0$$

If the $(m - 1)$ equations for the adjacent strands are added together we have,

$$\frac{\alpha d}{m} \left(\alpha a + 2 \tanh \frac{\alpha d}{2\,m} \right) \sum_1^{m-1} \sum_1^{p-1} I_{q_p} = \left(\frac{\frac{\alpha d}{m}}{\sinh \frac{\alpha d}{m}} + \frac{l_2}{l_1} \right) (I_{q_m} - I_{q1}) - (m - 1) \frac{\alpha d}{m} \left(\alpha a + 2 \tanh \frac{\alpha d}{m} \right) I_0$$

Therefore the flux in the q conductor when the strands are numbered in the direct order is,

$$\phi_q = \frac{1}{j\,\omega}\, \rho \frac{m}{w\,d}\, l_1 \Bigg[I\, \frac{\alpha d}{m} \left(\alpha a + \tanh \frac{\alpha d}{2\,m} \right) + \frac{\alpha d}{m} \left(\alpha a + 2 \tanh \frac{\alpha d}{2\,m} \right) m\, I_{b\,q1} + \left(\frac{\frac{\alpha d}{m}}{\sinh \frac{\alpha d}{m}} + \frac{l_2}{l_1} \right) (I_{q_m} - I_{q1}) - (m - 1) \frac{\alpha d}{m} \left(\alpha a + 2 \tanh \frac{\alpha d}{2\,m} \right) I_0 \Bigg] \tag{15}$$

If the strands are numbered in the reverse order, so that the first strand is at the top and the mth strand is at the bottom, the current in the conductor below the $q\,p$ strand is $I - \sum_1^p I_{q_p}$, and the $\sum_1^m I_{b\,q_p}$ is now:

$$\begin{aligned} \sum_1^m I_{b\,q_p} = & \; I_{b\,q_m} + I - I_{q1} \\ & + I_{b\,q_m} + I - (I_{q1} + I_{q2}) \\ & + I_{b\,q_m} + I - \sum_1^p I_{q_p} \\ & + \cdot \quad \cdot \quad \cdot \\ & + I_{b\,q_m} + I - I \\ = & \; m\,(I_{b\,q_m} + I) - \sum_1^{m-1} \sum_1^p I_{q_p} - I \\ = & \; m\, I_{b\,q_m} + (m - 1)\, I - \sum_1^{m-1} \sum_1^p I_{q_p} \end{aligned}$$

Therefore the flux in the q conductor when the strands are numbered in the reverse order is

$$\phi_q = \frac{1}{j\,\omega}\,\rho\,\frac{m}{w\,d}\,l_1\Bigg[I\,\frac{\alpha\,d}{m}\left(\alpha\,a + \tanh\frac{\alpha\,d}{2\,m}\right)$$

$$+ \frac{\alpha\,d}{m}\left(\alpha\,a + 2\tanh\frac{\alpha\,d}{2\,m}\right)(m\,I_{b\,q_m} + (m-1)\,I)$$

$$-\left(\frac{\frac{\alpha\,d}{m}}{\sinh\frac{\alpha\,d}{m}} + \frac{l_2}{l_1}\right)(I_{q_m} - I_{q_1})$$

$$+ (m-1)\,\frac{\alpha\,d}{m}\left(\alpha\,a + 2\tanh\frac{\alpha\,d}{2\,m}\right)I_0\Bigg] \qquad (16)$$

The loss in pressure as derived in equations (**13**) and (**14**) and the flux within a conductor depend upon the current in the top strand and the difference between the currents in the top and bottom strands. The current in the p strand is determined by equation (**11**).

The current in the top strand numbered in direct order, is I_{q_m}.

$$I_{q_m} = 2\sinh\frac{\beta\,d}{2\,m}\Bigg(I\,\frac{\cosh\frac{m-1/2}{m}\,\beta\,d}{\sinh\,\beta\,d}$$

$$- I_0\tanh\frac{\beta\,d}{2}\cosh\frac{m-1/2}{m}\,\beta\,d$$

$$+ I_0\sinh\frac{m-1/2}{m}\,\beta\,d\Bigg)$$

Expand in terms of $\beta\,d$ and $\frac{\beta\,d}{2\,m}$

$$I_{q_m} = 2\sinh^2\frac{\beta\,d}{2\,m}\left[I\left(\coth\,\beta\,d\coth\frac{\beta\,d}{2\,m} - 1\right)\right.$$

$$\left. + I_0\left(\tanh\frac{\beta\,d}{2}\coth\frac{\beta\,d}{2\,m} - 1\right)\right] \qquad (17)$$

Likewise:

$$I_{q_1} = 2\sinh^2\frac{\beta\,d}{2\,m}\left[I\,\frac{\coth\frac{\beta\,d}{2\,m}}{\sinh\,\beta\,d}\right.$$

$$\left. - I_0\left(\tanh\frac{\beta\,d}{2}\coth\frac{\beta\,d}{2\,m} - 1\right)\right]$$

Thus:

$$(I_{q_m} - I_{q_1}) = 2\sinh^2\frac{\beta\,d}{2\,m}\left[(I + 2\,I_0)\right.$$

$$\left.\left(\tanh\frac{\beta\,d}{2}\coth\frac{\beta\,d}{2\,m} - 1\right)\right] \qquad (18)$$

The pressure equations which determine the resistance and reactance drops, *viz.* equations (**13**) to (**16**) inclusive are in terms of these currents in the top and bottom strands in addition to the conductor current and the current I_0. We will rewrite these equations, making the substitutions given in equations (**17**) and (**18**), and remembering that the I_{q_m} in (**17**) is the same as I_{q_1} in (**14**). We will also make the substitution shown in equation (**10a**).

Equation (**13**) becomes:

$$\text{drop} = \frac{\rho}{w\,d}\,l_1\Bigg[I\,\alpha\,d\,\frac{\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)}{\tanh\frac{\beta\,d}{2\,m}}\coth\,\beta\,d$$

$$+ I_0\,\alpha\,d\,\frac{\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)}{\tanh\frac{\beta d}{2\,m}}\tanh\frac{\beta\,d}{2}$$

$$+ (I_b - I_0)\,\alpha\,d\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)$$

$$+ (I + I_b)\,\alpha\,d\,.\,\frac{\alpha\,a}{2}\Bigg] \qquad (13a)$$

Equation (**14**) becomes:

$$\text{drop} = \frac{\rho}{w\,d}\,l_1\Bigg[I\,\alpha\,d\,\frac{\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)}{\tanh\frac{\beta\,d}{2\,m}}\coth\,\beta\,d$$

$$+ I_0\,\alpha\,d\,\frac{\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)}{\tanh\frac{\beta\,d}{2\,m}}\tanh\frac{\beta\,d}{2}$$

$$- (I_b + I_0 + I)\,\alpha\,d\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)$$

$$+ I_b\,\alpha\,d\,.\,\frac{\alpha\,a}{2}\Bigg] \qquad (14a)$$

Equation (**15**) becomes:

$$\phi_q = \frac{1}{j\,\omega}\,\frac{\rho}{w\,d}\,l_1\Bigg[(I + 2\,I_0)$$

$$\alpha\,d\,\frac{\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)}{\tanh\frac{\beta\,d}{2\,m}}\tanh\frac{\beta\,d}{2}$$

$$+ (I_b - I_0)\,2\,m\,\alpha\,d\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)$$

$$+ I\,\alpha\,d\,.\,\frac{\alpha\,a}{2}\Bigg] \qquad (15a)$$

Equation (**16**) becomes:

$$\phi_q = \frac{1}{j\,\omega}\,\frac{\rho}{w\,d}\,l_1\Bigg[-(I + 2\,I_0)$$

$$\alpha\,d\,\frac{\left(\frac{\alpha\,a}{2} + \tanh\frac{\alpha\,d}{2\,m}\right)}{\tanh\frac{\beta\,d}{2\,m}}\tanh\frac{\beta\,d}{2}$$

$$+ (I_b + I_0 + I)\, \alpha\, d\, 2\, m \left(\frac{\alpha\, a}{2} + \tanh \frac{\alpha\, d}{2\, m} \right)$$

$$\left. + I\, \alpha\, d\, . \frac{\alpha\, a}{2} \right] \qquad (16a)$$

In each of these four equations I_b is the current in the slot below the conductor in question.

The writing of these equations is much simplified if we let:

$$\frac{l_1}{l_1 + l_2}\, \alpha\, d\, \frac{\left(\dfrac{\alpha\, a}{2} + \tanh \dfrac{\alpha\, d}{2\, m} \right)}{\tanh \dfrac{\beta\, d}{2\, m}}\, \coth \beta\, d$$

$$= M' = M_r' + j\, M_x'$$

$$\frac{l_1}{l_1 + l_2}\, \alpha\, d\, \frac{\left(\dfrac{\alpha\, a}{2} + \tanh \dfrac{\alpha\, d}{2\, m} \right)}{\tanh \dfrac{\beta\, d}{2\, m}}\, 2 \tanh \frac{\beta\, d}{2}$$

$$= N' = N_r' + j\, N_x'$$

$$\frac{l_1}{l_1 + l_2}\, \alpha\, d\, 2\, m \left(\frac{\alpha\, a}{2} + \tanh \frac{\alpha\, d}{2\, m} \right)$$

$$= T' = T_r' + j\, T_x'$$

$$\frac{l_1}{l_1 + l_2}\, \alpha\, d\, \alpha\, a = S' = j\, \frac{8\, \pi^2\, \omega\, f}{\rho\, s}\, d\, a$$

and $\frac{\rho}{w d}\,(l_1 + l_2) = R$ (the d-c. resistance of a half turn)

These equations may now be rewritten in simplified form. The resistance drop per half turn in the top element of the top strand of a conductor (**13a**) becomes:

$$\text{drop} = R \left[I\, M' + \frac{I_0\, N'}{2} + (I_b - I_0)\, \frac{T'}{2\, m} \right.$$

$$\left. + (I + I_b)\, S'/2 \right] \qquad (13b)$$

If the strands are turned over in the end connections the resistance drop per half turn in the bottom element of the foregoing strand, which is now the lowest in the conductor (**14a**) becomes:

$$\text{drop} = R \left[I\, M' + \frac{I_0\, N'}{2} - (I_b + I_0 + I)\, \frac{T'}{2\, m} \right.$$

$$\left. + I_b\, S'/2 \right] \qquad (14b)$$

The average resistance drop per half turn for the six cases considered is obtained from these two equations. By definition I_0 has such a value that the term involving T' in this average resistance drop is zero in every case. In order to simplify the expression we will let I_e represent the coefficient of $S'/2$. The average resistance drop per half turn is:

$$\text{av. drop} = R \left(I\, M' + \frac{I_0\, N'}{2} + \frac{I_e\, S'}{2} \right) \qquad (19)$$

I_e is the average sum of the $(I + I_b)$'s in equation (**13a**) and the I_b's in equation (**14a**) taken in the proper combination.

Case 1. $I_e = I + (q - 1 + n\, \underline{/\, \theta})\, I$ upper coil side

$= (q + n\, \underline{/\, \theta})\, I$ upper coil side

$= q\, I$ lower coil side

Case 2. $I_e = 1/2 \{ [I + (q - 1 + n\, \underline{/\, \theta})\, I] + [I + (q - 1)\, I] \}$

$= (q + n/2\, \underline{/\, \theta})\, I$

Case 3. $I_e = 1/2 \{ [I + (q - 1 + n\, \underline{/\, \theta})\, I] + [\, (q - 1)\, I\,] \}$

$= (q - 1/2 + n/2 / \theta)\, I$

Case 4. $I_e = 1/n \sum_1^n (q + n/2 / \theta)\, I$

$$= \left(\frac{n + 1}{2} + n/2 / \theta \right) I$$

Case 5. $I_e = \frac{1}{2\, n} \Big[(1 + n\, \underline{/\, \theta}) + (O) + (1 + n\, \underline{/\, \theta}) + (1 + 1) + (1 + 2 + n\, \underline{/\, \theta}) + (2) + \text{etc.} \Big] I$

The first term within the parenthesis is the current in the conductor plus the current below the first conductor of the upper coil side (**13b**). The second term is the current below the first conductor of the lower coil side (**14b**). This is zero. The third term is the current below the second conductor of the upper coil side (**14b**). The fourth term is the current in the conductor plus the current below the second conductor of the lower coil side (**13b**). Notice that this expression for I_e may be written:

$$I_e = \frac{1}{2\, n} \Big[(1 + n\, \underline{/\, \theta}) + (3 + n\, \underline{/\, \theta}) + (5 + n\, \underline{/\, \theta}) + \ldots + (2\, n - 1 + n\, \underline{/\, \theta}) \Big) I$$

$$I_e = \frac{1}{2\, n} \sum_1^n (2\, q - 1 + n\, \underline{/\, \theta})\, I$$

$$I_e = n/2 + n/2\, \underline{/\, \theta})\, I$$

Case 6. $I_e = 1/n \sum_1^n (q - 1/2 + n/2\, \underline{/\, \theta})\, I$

$= (n/2 + n/2\, \underline{/\, \theta})\, I$

The pressure acting in all conductors below the q conductor due to flux within the latter is $j\, \omega\, \phi_q$. Written in the simplified form this (**15a**) becomes:

$$\text{drop} = R\, [\, (I/2 + I_0)\, N' + (I_b - I_0)\, T' + I/2\, S'\,] \qquad (15b)$$

If the strands are turned over in the end connections, the pressure due to flux within the next succeeding half turn (**16a**) becomes:

$$\text{drop} = R\, [\, - (I/2 + I_0)\, N' + (I_b + I_0 + I)\, T' + I/2\, S' \qquad (16b)$$

Reference to the preceding paper shows that these pressure expressions are similar to those already derived for solid and finely laminated conductors except for the added terms involving S'. M' replaces M, N' replaces N and T' replaces $\alpha^2 d^2$. The expressions become identica' in the limiting case of an infinite number of strands with no insulation between them.

CALCULATION OF COPPER LOSS

The method of calculation is the same as that used in the preceding paper.

Case 1. When the strands are joined at the beginning and end of a half turn the copper 'oss in the half turn is symbolically:

$$\begin{aligned} \text{loss} &= I \,.\, R\,(I\,M' + I_b/2\,N' + I_s 2\,S') \\ &\quad + I_b \,.\, R\,[\,(I/2 + I_s/2)\,N' + I/2\,S'] \end{aligned}$$

In this case notice that $I_b = I_0$

The first term is the power loss due to the current in the conductor and the resistance drop in the topmost element of the topmost strand. The second term is the power due to the current in the slot below this conductor and to the pressure acting on it produced by the flux within the conductor. Expanding this expression gives:

$$\begin{aligned} \text{power} &= I \,.\, R\,I\,M' + I \,.\, R\,\frac{I_b}{2}\,N' + I \,.\, R\,\frac{I_s}{2}\,S' \\ &\quad + I_b \,.\, R\,\frac{I}{2}\,N' + I_b \,.\, R\,I_b\,N' + I_b \,.\, R\,\frac{I}{2}\,S'. \end{aligned}$$

The first term is $R\,I^2\,M_r'$. The sum of the second and fourth terms is $R\,I\,I_b\,N_r' \cos\theta_b$. The fifth term is $R\,I_b^2\,N_r'$ and since S' is a pure imaginary the sum of the third and sixth terms is zero. The expression for the power may be written:

$$\text{loss} = R\,[I^2\,M_r' + (I \,.\, I_b \cos\theta_b + I_b^2)\,N_r']$$

The phase angle θ_b is between the current, I, in the conductor and the total current, I_b, in the slot below it. Here the letters I and I_b represent the numerical values of the currents.

If this copper loss due to alternating current is divided by the loss due to the same amount of direct current, we obtain the ratio of alternating to direct-current resistance.

(a) The ratio of alternating to direct current resistance for a single half turn is:

$$K = \{M_r' + [\,(I_b/I)^2 + I_b/I \cos\theta_b]\,N_r'\}$$

(b) The average resistance ratio for a one-coil-side-per-slot winding having n layers is:

$$K = 1/n \sum_1^n \{M_r' + [\,(q-1)^2 + (q-1)\,]\,N_r'\}$$

$$= \left(M_r' + \frac{n^2-1}{3}\,N_r'\right)$$

(c) The average resistance ratio for the upper coil side of a two-coil-side-per-slot winding having n layers per coil side reduces to

$$K = \left[\,M_r' + \left(\frac{4\,n^2-1}{3} + n^2\cos\theta\right)N_r'\,\right]$$

θ is the phase angle between the currents in the upper and lower coil sides.

If the strands are joined at the beginning and end of a whole turn the loss ratio is a little more difficult to calculate inasmuch as the losses in the two half turns are different. There are two cases to consider, one in which the end connections are not turned over and one in which they are turned over.

Case 2. Strands joined at the beginning and end of a single turn; end connections not turned over. The heating loss in the whole turn may be expressed symbolically as:

$$\begin{aligned} \text{loss} &= 2\,I \,.\, R\,(I\,M' + I_0/2\,N' + I_s\,S'/2) \\ &\quad + I_b' \,.\, R\,[\,(I/2 + I_0)\,N' + (I_b' - I_0)\,T' \\ &\qquad\qquad + I/2\,S'] \\ &\quad + I_b'' \,.\, R\,[\,(I/2 + I_0)\,N' + (I_b'' - I_0,\,T' \\ &\qquad\qquad + I/2\,S'] \end{aligned}$$

The first term is the power due to the current in the conductor and the resistance drop in the top element o! the top strand of the turn. The second term is the power due to the current, I_b', below the upper half turn and the pressure produced by the flux within this half turn. Similarly the third term is the power due to the current, I_b'', below the lower half turn and the pressure produced by the flux within this half turn. For the q conductor, $I_b' = I\,(q - 1 + n\,/\underline{\theta})$ and $I_b'' = I\,(q-1)$. We have also shown that in this case (2) $I_s = I\,(q + n/2\,/\underline{\theta})$, and $I_0 = I\,(q - 1 + n/2\,/\underline{\theta})$.

As before θ is the phase angle between the currents in the upper and lower coil sides lying in the same slot. Making these substitutions and dividing by the direct-current resistance loss for a whole turn gives a resistance ratio per turn of

$$\begin{aligned} K = (M_r' &+ (q^2 - q + n^2/4 + (2\,q-1)\,n/2\cos\theta)\,N_r' \\ &\qquad + n^2/4\;\; T_r') \end{aligned}$$

The average value of this resistance ratio for a whole coil of n turns is

$$K = \left[\,M_r' + \left(\frac{7\,n^2-4}{12} + n^2/2\cos\theta\right)N_r' \right.$$
$$\left. \qquad + n^2/4\;\; T_r'\,\right]$$

Case 3. Strands joined at the beginning and end of a whole turn; end connections turned over. The heating loss for a whole turn is now:

$$\begin{aligned} \text{loss} &= 2\,I \,.\, R\,(I\,M' + I_0/2\;N' + I_s\;S'/2) \\ &\quad + I \,.\, R\,(-\,(I/2 + I_0)\,N' + (I_b'' + I_0 + I)\,T' \\ &\qquad\qquad + I\;\;S'/2 \\ &\quad + I_b'\,R\,[\,(I/2 + I_0)\,N' + (I_b' - I_0)\,T' \\ &\qquad\qquad + I\,S'/2\,] \end{aligned}$$

$$+ I_b'' \,.\, R\,[\,-\,(I/2 + I_0)\,N' + (I_b'' + I_0 + I)\,T' + I\,S'/2\,]$$

The first term is the power due to the current in the turn and the resistance drop in the top strand of the turn in the upper coil side and the bottom strand of the turn in the lower coil side. Due to the turning over of the end connections these two half-turn strands are a part of the same strand. The second term is the power due to the current in the turn and the pressure produced by the flux within the half turn that is in the lower coil side. The third term is the power due to the current below the half turn in the upper coil side and the pressure acting on this current that is produced by the flux within this half turn. The fourth term is similarly the power due to the current below the half turn in the lower coil side and the pressure acting on this current that is produced by the flux within this half turn. In this case:

$I_0 = (-1/2 + n/2\,\underline{/\theta}\,)\,I \quad I_b' = (q - 1 + n\,\underline{/\theta}\,)\,I$

$I_t = (q - 1/2 + n/2\,\underline{/\theta}\,)\,I \quad I_b'' = (q - 1)\,I$

Making these substitutions the resistance ratio for a whole turn reduces to:

$$K = \left\{ M_r' + \frac{n^2 - 1}{4} N_r' + \left[\,(2q-1)^2 + n^2 + 2\,(2q-1)\,n\cos\theta\,\right] T_r'/4 \right\}$$

The average resistance ratio for a whole coil of n turns is:

$$K = \left[M_r' + \frac{n^2 - 1}{4} N_r' + \left(\frac{7n^2 - 1}{12} + n^2/2 \cos\theta \right) T_r' \right]$$

The method of calculating the leakage impedance when the stranding is continuous throughout a whole coil is described in considerable detail in the preceding paper and need not be repeated here. With a finite number of strands, however, there are added terms involving S' which appear on account of the insulation between the strands. Fortunately their effect is not difficult to calculate.

The added resistance drop in a coil of n turns is (equation 19) $2\,n\,R\,I_t/2\,S'$. Values of I_t have already been calculated for the different cases. The added pressure acting in the coil side which lies in the bottom of the slot due to flux within the coil side above it is $n\,R\,(n\,\underline{/-\theta}\,)\,I/2\,S'$. The other added terms are those due to the pressure acting in the conductors of the coil produced by flux within the coil itself. There are three cases, *viz.*, 4, 5 and 6.

Case 4. When the end connections are not turned over the resistance drop taken is that in the upper element of the top strand of the conductors of both coil sides. The added drop is then:

$$\sum_1^n 2\,(q-1)\,R\,I/2\,S' \quad \text{or} \quad \frac{n\,(n-1)}{2} R\,I\,S'$$

Case 5. When the end connections are turned over on one side only the resistance drop taken is that in the top element of the top strand of the first half turn plus that in the bottom element of the bottom strand of the next half turn plus that in the bottom element of the bottom strand of the next half turn plus that in the top element of the top strand of the next half turn plus, etc. In this case it is readily shown that the added drop is:

$$\sum_1^n (2q-1)\;R\;I/2\;S' \quad \text{or} \quad n^2/2\;R\,I\,S'$$

Case 6. When the end connections are turned over on both sides the resistance drop taken is that in the top elements of the top strands of one coil side and the bottom elements of the bottom strands of the other coil side. The added pressure is thus

$$\sum_1^n (q-1)\,R\,I/2\,S' + \sum_1^n q\,R\;I/2\;S') \quad \text{or} \quad n^2/2\,R\,I\,S'$$

The sum of these three component added terms is the same in each of the three cases. It is $(n^2 + n^2 \cos\theta)$ $R\,I\,S'$.

The average value for a single half turn is $(n/2 + n/2 \cos\theta)\,R\,I\,S'$.

We may now write the expressions for the slot leakage impedance of a symmetrical pair of fractional pitch slots.

Refer to the preceding paper.

Case 4. End connections not turned over.

$$Z = R_c \left[M' + \left(\frac{2n^2 - 1}{4} + n^2/2 \cos\theta \right) N' + \frac{4n^2 - 1}{12} T' + (n/2 + n/2 \cos\theta)\,S' \right]$$

where R_c is the true resistance of a whole coil.

Case 5. End connections turned over on one side only. Even number of conductors per coil side.

$$Z = R_c \left[M' - N'/4 + \left(\frac{10n^2 - 1}{12} + n^2/2 \cos\theta \right) T' + (n/2 + n/2 \cos\theta)\,S' \right]$$

Case 5. Odd number of conductors per coil side.

$$Z = R_c \left[M' + \left(\frac{10n^2 - 1}{12} + n^2/2 \cos\theta \right) T' + (n/2 + n/2 \cos\theta)\,S' \right]$$

Case 6. End connections turned over on both sides.

$$Z = R_c \left[M' + \frac{n^2 - 1}{4} N' + \left(\frac{7n^2 - 1}{12} \right.\right.$$

$$+ n^2/2 \cos\theta \Big) T' + (n/2 + n/2 \cos\theta)\, S' \Big]$$

Since S' is pure imaginary, the terms involving it do not appear in the expressions for the alternating-current resistance. In the preceding paper $\alpha^2 d^2$ which is now replaced by T' was pure imaginary. T', however, has both real and imaginary parts, and thus adds to the value of the alternating-current resistance.

There follows a numerical calculation of the heat losses in a specified winding. The pitch of the coils is one and the dimensions of the slot and the conductors are:

Width of slot (s) .... = 2.54 cm.
Width of conductor (w) .... = 1.60 "
Length of armature core (l_1) .... = 72.4 "
Length of end turn (l_2) .... = 80.0 "
Depth of strand (d/m) .... = 0.254 "
Thickness of insulation between strands (a) .... = 0.0381 "
Number of strands per conductor (m) .. = 7.0
Number of conductors per coil side (n) .. = 2.0
Frequency (f) .... = 60 cycles
Average temperature of winding ...... = 100 deg. cent

$$\rho = 2260 \text{ c. g. s. ohms at 100 deg. cent.}$$

$$\alpha = 2\pi \sqrt{\frac{2 w f}{\rho s}}\,\underline{/\,45^\circ} = 1.15\,\underline{/\,45^\circ}$$

$$\frac{\alpha d}{m} = 0.292\,\underline{/\,45^\circ}$$

$$\frac{\alpha d}{2m} = 0.146\,\underline{/\,45^\circ}$$

$$\frac{\alpha a}{2} = 0.0219\,\underline{/\,45^\circ}$$

$$\tanh \frac{\alpha d}{2m} = 0.146\,\underline{/\,44^\circ\, 36.5'}$$ [4]

$$\frac{\dfrac{\alpha d}{m}}{\sinh \dfrac{\alpha d}{m}} = 1.00\,\underline{/-0.82}$$ [4]

$$\frac{T'}{4m^2} = \frac{\alpha d}{2m}\cdot\left(\frac{\alpha a}{2} + \tanh \frac{\alpha d}{2m}\right)$$

$$= 0.0245\,\underline{/\,89^\circ\, 38.5'}$$

From equation (10a)

$$\sinh \frac{\beta d}{2m} = \sqrt{\frac{\dfrac{\alpha d}{2m}\left(\dfrac{\alpha a}{2} + \tanh \dfrac{\alpha d}{2m}\right)}{\dfrac{\dfrac{\alpha d}{m}}{\sinh \dfrac{\alpha d}{m}} + \dfrac{l_2}{l_1}}}$$

$$\sinh \frac{\beta d}{2m} = \sqrt{\frac{0.0245\,\underline{/\,89^\circ\, 38.5'}}{1.0\,\underline{/-0.82^\circ} + 1.105}}$$

$$= \sqrt{0.01164\,\underline{/\,45^\circ\, 1.5'}}$$

$$= 0.07628 + j\, 0.07634$$

Let $\dfrac{\beta d}{2m} = g + j k$

$$\sinh (g + j k) = \sinh g \cos k + j \cosh g \sin k$$
$$= A + j B = C\,\underline{/\tanh^{-1} B/A}$$

That is $\sinh g \cos k = A$
$\cosh g \sin k = B$

Solving these two equations for g and k gives:

$$\sinh g = \sqrt{\frac{-(1 - C^2) + \sqrt{(1 - C^2)^2 + 4A^2}}{2}}$$

and $$\sin k = \sqrt{\frac{1 + C^2 - \sqrt{(1 + C^2)^2 - 4B^2}}{2}}$$

Substitution in these solutions shows that:

$\sinh g = 0.0766$ $g = 0.0767$
$\sin k = 0.0761$ $k = 0.0762$ radians

Therefore $$\frac{\beta d}{2m} = 0.108\,\underline{/\,44^\circ\, 50'}$$

$\tanh \dfrac{\beta d}{2m}$ is readily computed in this case from

$$\tanh \frac{\beta d}{2m} = \frac{\sinh \dfrac{\beta d}{2m}}{\sqrt{1 + \sinh^2 \dfrac{\beta d}{2m}}}$$

$$= \frac{0.1079\,\underline{/\,45^\circ\, 1.5'}}{\sqrt{1 + 0.01164\,\underline{/\,90^\circ\, 3'}}}$$

$$= 0.1079\,\underline{/\,44^\circ\, 21.5'}$$

$$\alpha d\, \frac{\dfrac{\alpha a}{2} + \tanh \dfrac{\alpha d}{2m}}{\tanh \dfrac{\beta d}{2m}} = 3.18\,\underline{/\,45^\circ\, 19'}$$

The values of $\coth \beta d$ and $2 \tanh \dfrac{\beta d}{2}$ can be computed from the formulas:

$\coth \beta d$

$$= \frac{\sinh 2mg \cosh 2mg - j \sin 2mk \cos 2mk}{\sinh^2 2mg \cos^2 2mk + \cosh^2 2mg \sin^2 2mk}$$

$2 \tanh \dfrac{\beta d}{2}$

$$= 2\, \frac{\sinh mg \cosh mg + j \sin mk \cos mk}{\cosh^2 mg \cos^2 mk + \sinh^2 mg \sin^2 mk}$$

From which

$$\coth \beta d = 0.8835\,\underline{/-11^\circ\, 20'}$$

$$2 \tanh \frac{\beta d}{2} = 1.472\,\underline{/\,34^\circ\, 7'}$$

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[4] From Kennelly's "Tables of Complex Hyperbolic and Circular Functions."

The complex quantities M', N' and T' may now be calculated

$$M' = 1.335 \,/\underline{33° 59} \quad = 1.11 \; + j\,0.746$$
$$N' = 2.22 \,/\underline{79° 26'} \quad = 0.408 + j\,2.19$$
$$T' = 2.28 \,/\underline{89° 38.5'} = 0.014 + j\,2.28$$

If the number of strands, m, is increased without limit while the depth of the conductor and the relative amount of insulation between the strands are unchanged we have:

$$\sinh \frac{\beta d}{2\,m} \doteq \frac{\beta\,d}{2\,m} \doteq \frac{\alpha\,d}{2\,m} \sqrt{\frac{a/d + 1}{l_2/l_1 + 1}}$$

since $\tanh \dfrac{\alpha\,d}{2\,m} \doteq \dfrac{\alpha\,d}{2\,m}$

and $$\frac{\dfrac{\alpha\,d}{m}}{\sinh \dfrac{\alpha\,d}{m}} \doteq 1$$

$$M' \doteq \beta\,d \coth \beta\,d$$

$$N' \doteq \beta\,d\,2 \tanh \frac{\beta\,d}{2}$$

For the winding we are considering,

$$\beta\,d \doteq 0.739\,\alpha\,d \doteq 1.51 \,/\underline{45°}$$

For this value of $\beta\,d$; $M_r' = 1.11$ and $N_r' = 0.413$. In this case, since T' is pure imaginary, $T_r' = 0$.

A further calculation has been made for conductors of the same net cross-section, but consisting of three strands instead of seven. In this case:

$$M' = 1.295 \,/\underline{33° 9'} \qquad M_r' = 1.084$$
$$N' = 2.04 \,/\underline{80° 52'} \qquad N_r' = 0.324$$
$$T' = 2.086 \,/\underline{87° 52'} \qquad T_r' = 0.0776$$

The following is a table of the ratios of alternating to direct-current resistance for this winding for each of the six strand arrangements.

Strand Arrangement	Resistance Ratio		
	$m = \alpha$	$m = 7$	$m = 3$
Case 1	3.17	3.15	2.70
" 2	2.76	2.75	2.46
" 3	1.42	1.47	1.66
" 4	2.66	2.06	2.40
" 5	1.01	1.08	1.41
" 6	1.42	1.47	1.66

Discussion

W. V. Lyon (by letter): A series of curves has been plotted which, though they may not be of particular value themselves, indicate a line of investigation that should prove of considerable importance. Curves similar to them have been discussed by Rogowski and others.

The curves marked "I" are for the upper bar of a laminated bar winding, with two bars per slot.

The curves marked "II" are the average values for the slot. Laminated conductors with laminations joined at the beginning and end of each turn. Two turns per coil, two coil sides per slot.

The curves marked "III" are the average values for the slot. The winding is exactly like the preceding case but the end connections are turned over.

The curves marked "IV" are the average values for the slot. Laminated coil with laminations joined at the beginning and end of the coil. Two turns per coil, two coil sides per slot. End connections turned over.

All of these curves are plotted for full-pitch, finely laminated windings. The length of the armature core is assumed equal to the length of one end connection. The ordinates of these curves show relative values only. The abscissas, $\alpha\,d$, are roughly equal to the depth of the conductor in centimeters for a frequency of 60 cycles.

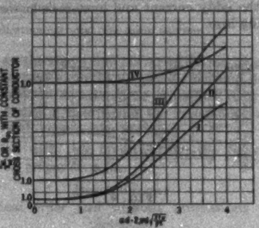

Fig. 1

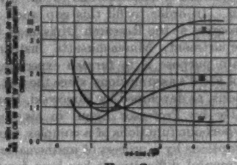

Fig. 2

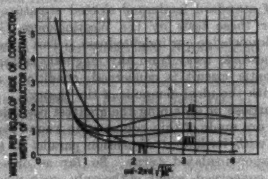

Fig. 3

Fig. 1 shows how entirely inappropriate laminated bar windings are when the conductors are deeper than about one centimeter. Fig. 2 shows that with conductors of constant width there is a depth which makes the alternating-current resistance a minimum. This has been called the critical depth. Notice that with the better types of windings, viz. III and IV, the critical depth is greater. The ordinates of those curves may also represent the watts per square centimeter of coil side for conductors of constant cross section. If all of the heat developed in the conductors passed through the *sides* of the coil, which of course it does not, these curves would show a truly critical depth.

If the width of the conductor is kept constant the watts per square centimeter of coil side do not reach as distinct a minimum value. In fact in the better windings, III and IV there is no minimum, *i. e.,* critical depth. Fig. 3.

Taking the surface through which the heat is conducted from the coil as the entire perimeter of the cross section of the coil the watts per square centimeter of insulation are plotted in Fig. 4. These curves were plotted for cases in which the cross section of the conductors was nine square centimeters and the thickness of the insulation was one-half a centimeter.

It seems that these curves only emphasize the need of a thorough investigation of the heat conduction through the insulation of embedded conductors. The problem is further complicated in that the best shape of conductor must be determined by considering not only the heat generated within it but also by the eddy current and hysteresis losses produced in the neighboring iron.

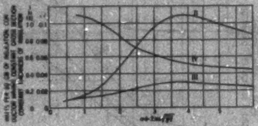

Fig. 4

M. S. Vallarta (by letter): Although a few resistance-ratio and temperature measurements have occasionally been reported, no thorough experimental investigation of the Field theory of skin-effect in embedded conductors has to our knowledge ever been undertaken. In order to fill this gap, such an investigation is now in progress at the Research Division of the Electrical Engineering Department, Massachusetts Institute of Technology. Its main purpose is to furnish experimental proof of the correctness of Field's assumptions, since the rest of the theory and its applications, as developed by Rogowski, Richter, Gilman and very recently by Professor Lyon, in his simple method involving the hyperbolic functions of a complex variable, follow from these assumptions by a process of mathematical deduction. Owing to experimental difficulties it has been found necessary, however, to test both the assumptions and the conclusions, as a check on the complete theory.

A piece of standard laminated slotted armature was kindly furnished for these tests by the Westinghouse Company, to which we acknowledge our indebtedness. This is mounted on a wooden framework, away from any magnetic material. So far as the magnetic circuit is concerned, conditions are in close agreement with the ideal demands of the theory.

For the purpose of obtaining the greatest possible resistance, the test coils are made of thin copper strip wound longitudinally in the slots, with its largest dimension parallel to the slot side and with paper-insulated turns. So far as one-dimensional skin-effect is concerned, which is the only one considered in the Field theory, these coils are the exact equivalent of a solid bar conductor of the same dimensions. Stranded conductors with twisted end connections have not been thus far experimentally investigated.

To test the assumption that an element of current in the slot produces no field below it, an exploring coil was placed longitudinally in the slot, with its plane parallel to the slot side, below a current carrying conductor. This exploring coil was connected through a shielded two-step vacuum tube amplifying circuit and thermocouple to a sensitive galvanometer. No deflection could in any case be obtained, thus confirming the assumption. No satisfactory proof of Field's assumption of no component of field strength parallel to the slot side has been found.

An experimental curve of cross-flux distribution was determined by winding five equi-distant exploring coils around the tooth and measuring the voltage induced in them when an alternating current flows through the slot conductors. This voltage was measured by connecting the exploring coils in turn to a sensitive galvanometer through a shielded two-step vacuum tube amplifying circuit and thermocouple. To eliminate tooth-tip leakage, an exploring coil at the top of the slot was always connected in series opposition with the coil through which the flux was measured.

The curve of cross-flux distribution is easily calculated from equation four of Professor Lyon's first paper. The flux linking an exploring coil distance x from the bottom of the upper conductor is

$$\phi_1 = \int_{x}^{d} \frac{4\pi l}{s} \left[\int_{0}^{x} w\,c\,dx + I_2 \right] dx$$

where $c = f(x)$ is given by the equation quoted above, *i. e.,*

$$c = \alpha / w \left[I_1 \frac{\cosh \alpha x}{\sinh \alpha d} - I_2 \tanh \frac{\alpha d}{2} \cosh \alpha x + I_2 \sinh \alpha x \right]$$

It follows by integration, if $I_1 = I_2 = I$.

$$\phi_1 = \frac{4\pi l I}{\alpha s} \left[\coth \alpha d - \frac{\cosh \alpha x}{\sinh \alpha d} - \tanh \frac{\alpha d}{2} (\cosh \alpha d - \cosh \alpha x) + \sinh \alpha d - \sinh \alpha x \right]$$

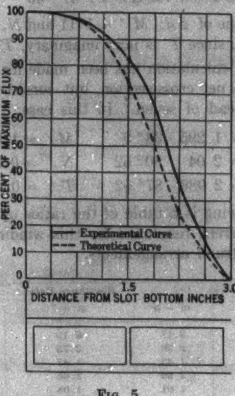

Fig. 5

For the lower conductor alone:

$$\phi_2 = \int_{x}^{d} \frac{4\pi l}{s} \left[\int_{0}^{x} w\,c\,dx \right] dx$$

with

$$c = \frac{\alpha I}{w} \quad \frac{\cosh \alpha x}{\sinh \alpha d}$$

whence

$$\phi_2 = \frac{4\pi l I}{\alpha s} \left[\coth \alpha d - \frac{\cosh \alpha x}{\sinh \alpha d} \right]$$

Let ϕ_{10} be the total flux linking an exploring coil at the bottom of the upper conductor. The total flux linking an exploring coil distance x from the bottom of the slot is:

$$\phi = \phi_{10} + \phi_1$$

From which the flux at any point along the lower conductor can be calculated.

The experimental and calculated curves of cross-flux distribution are given in Fig. 5. The agreement is considered satisfactory, within the limits of experimental error.

Resistance-ratio measurements have also been made. Power is measured by the three-voltmeter method, especial precautions being taken to have a sinusoidal voltage wave. Oscillographic records show that this condition was in every case closely fulfilled. The disturbing effect of uneven temperature distribution is largely eliminated by operating only after a steady uniform temperature, such as caused by a direct current, has been reached, then making all a-c. measurements within a short interval. To correct for iron loss, a coil of fine magnet wire was wound around the teeth, the excitation being distributed so as to correspond as closely as possible with conditions in the slot conductors. Phase difference effects of course cannot be imitated with this arrangement. The skin effect of such a winding is assumed to be negligible.

Results of resistance-ratio measurements and computation data are given below. Each power measurement given is the average of at least five runs. The precision of individual measurements is estimated at one per cent or better.

COMPUTATION DATA

Dimensions of slot:	Width	1.905	cm.
	Length	40.6	cm.
	Depth	7.62	cm.
Effective width of conductor		1.418	cm.
Effective height of conductor		3.58	cm.
	Frequency	60.0	cycles
	Temperature	65	deg. cent.

TABLE I

	Measurements for two conductors in series				
Measured power watts	Current amperes	Correction for end turns watts [1]	Correction for iron loss watts	Net power watts	A-C. resistance ohms
204.9	9.14	3.84	6.05	195.0	2.34
68.0	5.21	1.22	2.21	64.6	2.38
11.53	2.131	0.20	0.50	10.83	2.39
3.32	1.136	0.05	0.22	3.05	2.38
				Average	2.37 ohms
				Embedded portion d-c. resistance	0.2251 ohms
				Resistance ratio	10.52
				Calculated resistance ratio	10.26
				Difference	2.5%

TABLE II [2]

	Measurements for lower conductor				
Measured power watts	Current amperes	Correction for end turns watts [1]	Correction for iron loss watts	Net power watts	A-C. resistance ohms
95.8	15.16	5.25	3.14	87.4	0.382
34.9	9.16	1.92	1.21	31.7	0.378
11.81	5.32	0.65	0.37	10.79	0.381
1.98	2.21	0.00	0.05	1.84	0.377
				Average	0.3795 ohms
				Embedded portion d-c. resistance	0.1148 ohms
				Resistance ratio	3.30
				Calculated resistance ratio	3.25
				Difference	2.0%

TABLE III [3]

	Measurements for upper conductor				
Measured power watts	Current amperes	Correction for end turns watts [1]	Correction for iron loss watts	Net power watts	A-C. resistance ohms
181.5	9.36	2.15	2.36	177.0	2.04
62.7	5.47	0.74	1.54	60.4	2.01
10.17	2.145	0.11	0.46	9.60	1.98
2.70	1.140	0.03	0.07	2.60	2.00
				Average	2.01 ohms
				Embedded portion d-c. resistance	0.1110 ohms
				Resistance ratio	18.1
				Calculated resistance ratio	17.27
				Difference	4.8%

It is seen from the above that, as far as can be judged from our present evidence, the complex hyperbolic method developed by Prof. Lyon correctly describes the cross-flux distribution and gives simple means of computing the resistance ratio of ideal bar windings with engineering accuracy.

In connection with this investigation, the following bibliography has been prepared:

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12. R. Richter. "Uber zusätzliche Stromwärme. II: Entwurf von Nutenwicklungen." *Arch. für Elek.* IV, 1, 1915.

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15. R. Richter. "Uber zusätzliche Stromwärme. III: Nutenwicklungen mit unterteilten Leitern." *Arch. für Elek.* V, 1, 1916.

16. L. Roebel. German Patent 277012.

17. R. Richter. "Uber zusätzliche Stromwärme. IV: Unterdrückung durch magentische Hilfskreise." *Arch. für Elek.* V, 335, 1917.

18. W. V. Lyon. "Current Distribution in Armature Conductors." Bulletin 19. Res. Div. Elec. Eng. Dept. M. I. T. 1919.

19. A. E. Gilman. "Eddy-Current Losses in Armature Conductors." TRANS. A. I. E. E., Vol. XXXIX, 1920, Part I, p. 997.

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[1] Length of end turns is 20 per cent of total length. Correction assumes that skin effect in air for the coils is negligible, which is borne out by experiment.

[2] Lower conductor alone in slot.

[3] Both conductors carrying the same current.

20. H. W. Taylor. "Eddy-Currents in Stator Windings." *Jour. I. E. E.*, LVIII, 279, 1920.

21. R. Pohl. "Eine einfache Theorie der zusätzlichen Verluste im Nutenkuper von Wechselstrommaschinen." *Elekt. Zeit.* XLI, 908 and 997, 1920.

22. W. V. Lyon. "Heat Losses in the Conductors of A-C. Machines." TRANS. A. I. E. E., Vol. XL, 1921, p. 1361.

23. W. V. Lyon. "Heat Losses in Stranded Armature Conductors." JOUR. A. I. E. E., Vol. XLI, 1922, Jan., p. 37.

V. Karapetoff: Prof. Lyon deserves much credit for having worked out in detail various expressions for heat losses in armature conductors, with a non-uniform distribution of current. I wish only to point out some possible improvements in the fundamental mathematical treatment, and to indicate the next steps that might be taken in the solution of this important problem.

1. *Gilman's Work.* In June 1920 Mr. R. E. Gilman presented before the Institute a highly mathematical paper on the same subject (TRANS. Vol 39, p. 997), and it is to be regretted that in Prof. Lyon's paper, presented a year and a half later, before the same body, no attempt is made to correlate his work with that of Gilman's, and to point out identical results, discrepancies, if any, advantages and disadvantages of the two different methods of mathematical analysis. It remains for a future investigator to finish this part of the work.

2. *Exponential Notation.* In my discussion of Gilman's paper (*ibid*, p. 1054) the advantages of exponential notation are pointed out, and it is shown that several pages of long tedious formulas may be done away with, and that a solution of certain simultaneous equations is obviated. It now remains to compare the method of exponential notation with the use of hyperbolic functions of a complex variable, as used in Prof. Lyon's paper. In making this comparison, it is necessary to keep in mind that at the present time we have only Kennelly's tables of such functions, with steps of such magnitude that the two-directional interpolation is quite tedious. The building up of hyperbolic functions of a complex variable out of those of real variables also takes considerable time.

3. *The fundamental differential equation.* The fundamental differential equation of distribution of alternating-current density in a long conductor, subjected to a transverse magnetic flux, is not original either with Mr. Gilman or with Prof. Lyon. See, for example, A. Russell, Alternating Currents, Vol. I, index under "eddy currents." This equation can now be derived much more directly from Heaviside's laws of circuitation which are familiar to the younger generation of engineers. We want as wide a circle of readers for our Institute papers as possible, and any simplification in mathematics, any deduction directly from a general physical law, rather than by a special "follow me" method, is a step in the right direction.

4. *Some mathematical simplifications.* Prof. Lyon's paper being based on a well-known fundamental equation, the value of the contribution lies mainly in the application of the solution to certain specific cases. The solution must be in the simplest possible form for numerical computations. An inspection of his formulas shows the possibility of considerable further simplification. The formulas used in the present paper are based on equation (3) in his first paper (TRANS., 1921, Vol. 40, p. 1361), and it is therefore necessary to go back to that paper in order to indicate an alternative treatment.

The objections to Prof. Lyon's formulas are (a) that they are involved and unsymmetrical, and (b) that the variable x enters in the same formula in two or more places. What seems to be a simpler form of solution both for a general development and for numerical work, is indicated below; the equations numbers 1, 2 and 3, refer to Lyon's first paper:

Let the general solution of equation (2) be written in the form of

$$\underset{\cdot}{c} = (\alpha/w)\ \underset{\cdot}{D}\ \mathrm{Sinh}\ (\alpha\, y + \beta) \qquad (10)$$

This solution differs from equation (3) in the following respects: (a) the expression (α/w) is written out explicitly in order to simplify further transformations; (b) the variable distance, y, is assumed to be measured from the center of the conductor, in order to make the equations more symmetrical. In the original paper the corresponding variable, x, is measured from the lower edge; (c) the variable y enters in the equation only once, while equation (3) contains x twice; (d) The two constants of integration are D and β, that is, directly the amplitude and the phase, instead of the components $\underset{\cdot}{A}$ and $\underset{\cdot}{B}$.

To determine $\underset{\cdot}{D}$ and β, we substitute expression (10) in equation (1), and in the formula for I_1*. After simplification we find:

$$\tanh \beta = [I_1/(I_1 + 2\, I_0)] \quad \mathrm{Coth}\ \alpha\, d/2 \qquad (11)$$

$$\underset{\cdot}{D} = \frac{1}{2}\, I_1/(\mathrm{Sinh}\ \beta\ \mathrm{Sinh}\ \alpha\, d/2) \qquad (12)$$

Equation (10), with the auxiliary expressions (11) and (12) leads to simpler formulas and computations than the formulas used in both of Prof. Lyon's papers. For the current density at the center of the conductor we have, putting $y = 0$,

$$\underset{\cdot}{c} = (\alpha/w)\ \underset{\cdot}{D}\ \mathrm{Sinh}\ \beta \qquad (13)$$

or, substituting for D its value from eq. (12),

$$\underset{\cdot}{c} = \alpha\, I_1/(2\, w\ \mathrm{Sinh}\ \alpha\, d/2) \qquad (14)$$

which checks with Prof. Lyon's expression.†

5. *Future Work.* There is no reason why this problem should not be brought now to a final solution, at least in application to standard turbo-alternators. By this I mean a set of curves, charts, tables, etc. with which a designer could safely compute the armature copper loss for an assumed arrangement of conductors. At the present stage the designer would have to study one or two highly mathematical articles and then perform rather long computations before he could get a specific result. Should he then decide to change his winding, much of the numerical work would have to be repeated.

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*TRANS. A. I. E. E., 1921, p. 1369.

†TRANS. A. I. E. E., 1921, p. 1372.

Current Locus of Single-Phase Induction Motors

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***Review of the Subject.**—The principal applications of the current locus of single-phase induction motors are the predetermination of the performance of a projected motor on the basis of its constants, and the determination of the performance and constants of an existing motor on the basis of a few simple tests. The first question is particularly attractive to a mathematically trained mind, because, with constants considered as known, it is simply a problem of mathematics; a great amount of work has been done to find and perfect its solution. The second problem is, perhaps, more difficult than the first. Its thorough treatment requires not only the knowledge of the solution of the first problem, but also the ability to make use of more or less complicated combinations of constants given by tests instead of the constants themselves; moreover, the exact solution usually cannot be obtained, and one is obliged to make certain incorrect assumptions, drawing upon the practical experience to set proper limits to these inaccuracies; for this reason, perhaps, the second problem has always been less popular with investigators than the first, and the available results still leave room for improvement, especially in connection with the "tilted" diagram.*

In what follows this problem is treated by a method which is believed to combine the accuracy with comparative simplicity of the final results—the latter, at least, to the extent which can reasonably be expected when dealing with an apparatus of such inherent complexity as the single-phase induction motor.

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Current Locus Diagram

The diagram will be based on the circuit of Fig. 1 which expresses the equivalence of the single-phase motor to two polyphase motors with primary windings connected in series.[1] The exciting impedance consists of a reactance X divided between the two stators; the core loss circuit g is connected across the line; no specific assumption is made as to the nature of the loss in an elliptical field, the current covering this loss being always too small to have an appreciable influence on the phase relation and the magnitude of the vectors of the diagram.

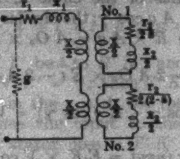

Fig. 1

In Fig. 2 let $O\,I$ be the current I' in the motor branch $r_1 - x_1 - X/2 - X/2$; the line voltage V' is the sum of $O\,R' = r_1\,I'$, $R'\,S' = x_1\,I'$, $S'\,M' = X/2\,I'$, $M'\,N' = X/2\,I'$, and of the e. m. fs. $M'\,P' = X/2\,I_2'$ and $N'\,Q' = X/2\,I_2''$ due to the reaction of the currents I_2' and I_2'' set up in the rotor circuits No. 1 and No. 2 by the e. m. fs. $S'\,M'$ and $M'\,N'$. Electromotive forces $M'\,P'$ and $N'\,Q'$ result from the diagram of Fig. 2 in which

$$S'\,F' = \frac{r_2\,I_2'}{2\,s}\,,\quad F'\,M' = \frac{X + x_2}{2}\,I_2'\,,$$

$$M'\,H' = \frac{r_2\,I_2''}{2\,(2-s)}\,,\quad H'\,N' = \frac{X + x_2}{2}\,I_2''\,.$$

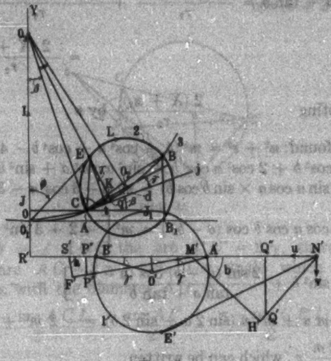

Fig. 2

$$\text{Let}\qquad z_1^2 = \frac{r_2^2}{4\,s^2} + \left(\frac{X + x_2}{2}\right)^2$$

$$\text{and}\qquad z_2^2 = \frac{r_2^2}{4\,(2-s)^2} + \left(\frac{X + x_2}{2}\right)^2;$$

$$\text{then (Fig. 2)}\quad \sin a = \frac{X + x_2}{2\,z_1}\,,\ \cos a = \frac{r_2}{2\,s\,z_1}\,,$$

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[1] The cross field theory leads to the same circuit. See V. Karapetoff, Journal A. I. E. E., August, 1921, p. 640. The primary and secondary windings are usually combined in a divided circuit instead of being left in inductive relation by means of 1 to 1 ratio transformers, as in Fig. 1.

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$$\sin b = \frac{X + x_2}{2\,z_2},\ \cos b = \frac{r_2}{2\,(2 - s)\,z_2}.$$

If the current I' remains constant, the point N' is fixed, and the locus of the line voltage is described by the sum $N' E'$ of the vectors $M' P'$ and $N' Q'$. Let N' be the origin of coordinates u and v, with axes directed to the left and downwards, as shown; projections of $M' P'$ on these axes are:

$$M' P'' = M' P' \sin a = M' F' \frac{X}{X + x_2} \sin a$$

$$= S' M' \frac{X}{X + x_2} \sin^2 a = \frac{X}{2} \times \frac{X}{X + x_2} I' \sin^2 a\,;$$

and $M' P' \cos a = \dfrac{X}{2} \times \dfrac{X}{X + x_2} I' \sin a \times \cos a$

respectively; the e. m. f. $N' Q'$ gives for its projections similar expressions with the angle b instead of a; therefore, denoting

$$\frac{X^2 I'}{2\,(X + x_2)} \text{ by } m,$$

the coordinates of E' are $u = m\,(\sin^2 a + \sin^2 b) = m\,(2 - \cos^2 a - \cos^2 b)$ and $v = m\,(\sin a \cos a + \sin b \cos b)$. The equation of the locus of E' is obtained by eliminating a and b between these expressions and the following relation:

$$\tan a + \tan b = \frac{(X + x_2)\,s}{r_2} + \frac{(X + x_2)\,(2 - s)}{r_2} = \frac{2\,(X + x_2)}{r_2}\,;$$

denoting $\dfrac{2\,(X + x_2)}{r_2}$ by n,

it is found: $u^2 + v^2 = m^2\,(4 + \cos^4 a + \cos^4 b - 4 \cos^2 a - 4 \cos^2 b + 2 \cos^2 a \cos^2 b + \sin^2 a \cos^2 a + \sin^2 b \cos^2 b + 2 \sin a \cos a \times \sin b \cos b) = m^2\,[4 - 3 \cos^2 a - 3 \cos^2 b + 2 \cos a \cos b \cos (a - b)\,] = m^2 \left[-2 + 3 \sin^2 a + 3 \sin^2 b + \dfrac{2 \sin (a + b) \cos (a - b)}{\tan a + \tan b} \right] = -\,2\,m^2 + 3\,m\,u + m^2/n\,(\sin 2\,a + \sin 2\,b) = -\,2\,m^2 + 3\,m\,u + \dfrac{2\,m}{n}\,v$, which can be written:

$\left(u - \dfrac{3\,m}{2}\right)^2 + (v - m/n)^2 = m^2\,(1/4 + 1/n^2)$, and shows that the locus is a circle 1 with the point O' of coordinates $u_0 = \dfrac{3\,m}{2}$, $v_0 = m/n$ as center. For $v = 0$ the equation gives $u = \dfrac{3\,m}{2} \pm m/2$, i. e. $N' A' = m$, $N' B' = 2\,m$. At B', $u = m\,(\sin^2 a + \sin^2 b) = 2\,m$, i. e. $\sin a = \sin b = 1$, which is possible only if $s = \infty$ at this point.

The current locus at constant voltage V is derived from the circle 1 by inversion with O as center and $V I'$ as constant of inversion, followed by the substitution for the inverse figure of its image with respect to $O\,Y$; this gives a circle 2 of center O_2. If the core loss is constant, the locus of the entire circuit of Fig. 1 is the circle 2 referred to an origin O_1 such that $O_1 O$ = current in the branch g.

The inverse of the line $R' N'$ is a circle 3 of diameter $= \dfrac{V I'}{O R'} = \dfrac{V}{r_1}$, having its center O_3 on $O\,Y$; let γ be the angle which the radius $A\,O_3$ at A (corresponding to A') makes with the tangent $A\,j$ to the circle 3; this angle is equal to the angle $B' A' O'$; therefore,

$$\tan \gamma = v_0 : \frac{A' B'}{2} = \frac{2}{n} = \frac{r_2}{X + x_2} \tag{1}$$

INPUT TO THE ROTOR[2]

At a point E of the circle 2 let $E\,q$ be ⊥ to $A\,O_2$ and $E\,t$ ⊥ to $A\,j$; the triangles $O\,O_2\,E$ and $A\,O_2\,E$ having a common side $O_2\,E$ give $2\,A\,O_2 \times E\,t - A\,E^2 = 2\,O\,O_2 \times O\,E \times \cos \phi - O\,E^2 = \dfrac{V\,I \cos \phi}{r_1} - I^2$

$$= \frac{\text{rotor input}}{r_1}.$$

If R is the radius of the circle 2, then $A\,E^2 = 2\,R \times A\,d = 2\,R \times A\,q \cos \gamma$; the similar triangles $A\,O_3\,O_2$ and $A\,K\,q$ give $R \times A\,q = A\,O_3 \times K\,q$, hence,

$$\frac{\text{rotor input}}{r_1} = 2\,A\,O_3 \times E\,t - 2\,A\,O_3 \times K\,q \cos \gamma$$

$$= 2\,A\,O_3\,(E\,q \cos \gamma - K\,q \cos \gamma) = V/r_1 \times E\,K \cos \gamma, \text{ i. e.}$$

$$\textit{Rotor input} = E\,K \times V \cos \gamma \tag{2}$$

or, since γ is always very small:

$$\textit{Rotor input} = \sim E\,K \times V \tag{2a}$$

As will be seen, the graphical expressions of the performance elements are very simple in the constant current diagram (denoted "c. c. d."); they will be used for the derivation of the much less obvious relations in the constant voltage diagram ("c. v. d."). Since the current I' is arbitrary, it is convenient to simplify the figures by giving it such a value that the inverse of the circle 1 is equal to the circle 1 itself, which may then be considered both as the voltage locus at constant current, and—disregarding its incorrect location with respect to $O\,Y$—as the current locus at constant voltage. Plain capitals A, B, etc., will refer to the points of the c. v. d.; the same capitals with an accent, A', B', etc., will be used for the corresponding points of the c. c. d.; two corresponding points of the circle, such as A and A' are on the same line passing through O. The voltage and the current will be denoted by V and I in the c. v. d., and by V' and I' in the c. c. d.; it is clear that at the corresponding points $V'/V = I'/I$.

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[2] It is known that the primary and secondary outputs at a point E are proportional to the distances of E from the lines passing through the points of zero outputs (lines $A\,B$ and $C\,L$ in the figures). The purpose of the demonstration given below is to determine the coefficients of proportionality in equations (2) and (3) and to establish equations (2a) and (3a) whose simplicity facilitates the use of the tilted diagram.

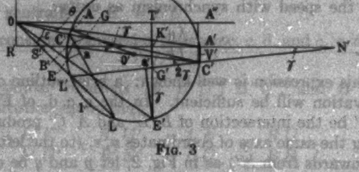

Fig. 3

In the triangles $M' F' S'$ and $M' P' P''$, Fig. 2, $M' P' \times M' F' = M' S' \times M' P''$; but $M' F'$

$$= \frac{X + x_2}{X} \times M' P', \quad M' P' = X/2\, I_2', \text{ and } M' S'$$

$$= X/2\, I', \text{ therefore, } I_2'^2 = \frac{2I' \times M' P''}{X + x_2};$$

similarly,
$$I_2''^2 = \frac{2\, I' \times N' Q''}{X + x_2};$$

hence $r_2/2\, (I_2'^2 + I_2''^2)$ = rotor copper loss

$$= \frac{r_2\, I'}{X + x_2} \times u = I'\, u \tan \gamma \; (u = \text{abscissa of } E').$$

In Fig. 3 let $E' T'$ be ⊥ to $R' N'$, and $N' C' L'$ a line such that $\angle A' N' C' = \gamma$; then $G' K' = N' K' \tan \gamma = u \tan \gamma$, i. e. in the c. c. d. the rotor copper loss is $G' K' \times I'$. Since the input to the motor is $T' E' \times I'$, and the stator loss $= T' K' \times I'$, the rotor input is $K' E' \times I'$, and the rotor output $= G' E' \times I'$. At L' and C', $G' E' = O$; these points are the locked[3] and the no-load points (= zero — torque points) respectively. $A' C'$ is ⊥ to $R' N'$ because $B' A' = A' N'$; therefore, in the c. c. d. the rotor loss is the same at A' and C'; but at C' the stator supplies both its own loss $A' A'' \times I'$ and the rotor loss; at A' the latter must be supplied externally, as mechanical power. At synchronism (point U') $s = O$, $\cos a = O$, and v/u

$$= \frac{m \sin b \times \cos b}{m \sin^2 b} = \frac{r_2}{2\,(X + x_2)} = 1/2 \tan \gamma,$$

i. e. U' is the middle of the vertical segment (not shown) passing through U' and representing the rotor loss at U'; this expresses the well-known fact that at synchronous speed the stator supplies one-half of the rotor loss; the other half must be supplied externally.

Rotor Output

Let (Fig. 3) $E' a'$ be ⊥ to $C' L'$ and $E a$ ⊥ to $C L$; in Fig. 3a (giving details of Fig. 3) the inscribed triangles $C E L$ and $C' E' L'$ give:

$$\frac{E' a'}{E a} = \frac{E' C' \times E' L'}{E C \times E L}; \text{ but } \frac{E' C'}{E C} = \frac{O E'}{O C};$$

$$\frac{E' L'}{E L} = \frac{O L'}{O E}; \text{ and } \frac{O L'}{O C} = \frac{L' C'}{L C};$$

$$\text{hence } \frac{E' a'}{E a} = \frac{O E'}{O E} \times \frac{L' C'}{L C} = \frac{V'}{I} \times \frac{L' C'}{L C}.$$

The rotor output at E' is

$$E' G' \times I' = \frac{E' a' \times I'}{\cos \gamma};$$

therefore, the rotor output at E in the c. v. d. is

$$\left(\frac{E' a' \times I'}{\cos \gamma}\right) \times \left(\frac{V}{V'}\right)^2 = \frac{E a \times V}{\cos \gamma} \times \frac{L' C'}{L C}.$$

In Fig. 3 let $\epsilon = \angle C O L$; the arc $B' E L'$ is measured by 4γ; the arc $L' E' C' = B' E' C' - B' E L' = \pi - 4 \gamma$; therefore, the arc $C E L$ = arc $C L'$ + arc $L' L$ $= (C' E' L - 2 \epsilon) + (L' E' C' - C' E' L) = -2 \epsilon + L' E' C' = \pi - 4 \gamma - 2 \epsilon$;

$$\text{hence, } \frac{L' C'}{L C} = \frac{\sin {}^1\!/\!_2\, (\pi - 4 \gamma)}{\sin {}^1\!/\!_2\, (\pi - 4 \gamma - 2 \epsilon)}$$

$$= \frac{\cos 2 \gamma}{\cos (\epsilon + 2 \gamma)}.$$

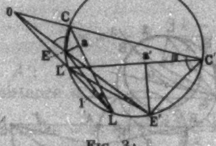

Fig. 3A

Let $\theta = \angle A O C$; the arc $A' C' = 2 \gamma$, therefore, the arc $A C = 2 \gamma - 2 \theta$. The angle which $C L$ makes with the diameter $A O'$ is

$$\frac{\pi - \text{arc } A C L}{2} - \frac{\text{arc } A C}{2} = \frac{\pi - \text{arc } C E L}{2}$$

$$- \text{arc } A C = \frac{\pi - (\pi - 4 \gamma - 2 \epsilon)}{2} - (2 \gamma - 2 \theta)$$

$$= \epsilon + 2 \theta;$$

if $E G$ is drawn ⊥ to $A O'$, then $E a = E G \times \cos (\epsilon + 2 \theta)$; substituting:

$$\textit{Rotor output} = E G \times V \times \frac{\cos 2 \gamma}{\cos \gamma} \times \frac{\cos (\epsilon + 2 \theta)}{\cos (\epsilon + 2 \gamma)} \quad (3)$$

The angles θ and γ are very small; moreover, θ

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[3] This can also be proved by making $s = 1$ in the expressions of u and v, which gives $\frac{v}{u} = \frac{r_2}{X + x_2} = \tan \gamma$.

differs from γ only by one-half of the negligibly small arc AC; both fractions in (3) are very close to unity (and differ from it in the opposite senses), therefore,

$$\textit{Rotor output} = \sim EG \times V \qquad (3a)$$

If the rotor resistance is very high, it may be advisable to measure γ, ϵ and θ on the diagram and use equation (3), but this is seldom necessary.

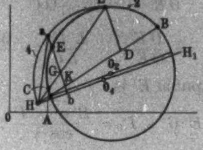

Fig. 4

Rotor Copper Loss

When equations (2a) and (3a) are applicable,[4] they give (Fig. 4)

$$\textit{Rotor copper loss} = EK \times V - EG \times V$$
$$= GK \times V \qquad (4a)$$

In Fig. 4 let H be the intersection of LC with BA, and 4 = a circle through H and L, with its center O_4 on HH_1 parallel to AO_2. Since GK is proportional to Hb and therefore proportional to Ha^2, the rotor loss $GK \times V$ is proportional to Ha^2. Let LD be ⊥ to AO_2; at L the rotor loss = rotor input = $\sim LD \times V$; therefore, the coefficient of proportionality is

$$V \times \frac{LD}{HL^2}:$$

$$\textit{Rotor copper loss} = \sim H a^2 \times \left(V \times \frac{LD}{HL^2} \right) \qquad (4b)$$

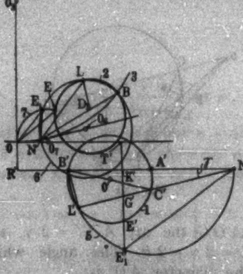

Fig. 4A

Expressions (2a), (3a) and (4a) show that *if representative segments of the rotor input, output and loss are drawn perpendicular to the diameter passing through the point of zero stator output, they can be read directly in amperes, as in the current locus of a polyphase motor.*[5] The expressions are, however, only approximate in the single-phase motor, although the accuracy is sufficient in most cases occurring in practise.

Speed

Let $a\,a$ (c. v. d. in Fig. 5) be an arbitrary line parallel to the tangent at B ($s = \infty$), and f, g, h, the points of intersection of this line with BL, BE and BU respectively (U = point of synchronous speed); then, if S is the speed with synchronism as unity:

$$S = \frac{fg}{fh} \qquad (5)$$

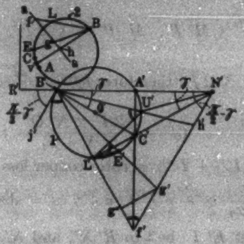

Fig. 5

This expression is well-known; a brief outline of its derivation will be sufficient. In the c. c. d. of Fig. 5 let f' be the intersection of $B'L'$ and $A'C'$ produced; using the same axes of coordinates u, v, (to the left and downwards from N') as in Fig. 2, let p and q be coordinates of a point E'; the equation of $N'f'$ is $v = u \times \cot\gamma$; the equation of $B'E'$ is $q(u - 2m) = v(p - 2m)$; these equations give for the coordinates u_1 and v_1 of g':

$$u_1 = \frac{2mq\tan\gamma}{q\tan\gamma + 2m - p},$$

$$v_1 = \frac{2mq}{q\tan\gamma + 2m - p}.$$

The equation of $B'f'$ is $u + v \times \tan\gamma - 2m = O$; therefore, the distance $g''g'$ of g' from $B'f'$ is proportional to $u_1 + v_1\tan\gamma - 2m$; but, in connection with Fig. 2 it was found: $p = m(\sin^2 a + \sin^2 b)$; $q = m(\sin a \cos a + \sin b \cos b)$ hence, substituting, $g''g'$ is proportional to

$$\frac{\tan\gamma(\sin a\cos a + \sin b\cos b) - \cos^2 a - \cos^2 b}{\tan\gamma(\sin a\cos a + \sin b\cos b) + \cos^2 a + \cos^2 b}$$

substituting for $\tan\gamma$, $\sin a$, etc. their expressions as functions of the slip and the constants of the motor gives, after some transformations: $g''g'$ is proportional to $(1 - s)^2$ and to S^2; therefore, $f'g'$ is proportional to S^2, and, if U' is the point of synchronous speed,

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[4] See Appendix 1 for the exact expression of the rotor copper loss.

[5] Journal A. I. E. E., April 1921, p. 329.

$$S^2 = \frac{f'g'}{f'h'}.$$

It can easily be seen that $N'f'$ is parallel to the tangent $B'j'$ at B'; the triangles $B'L'E'$ and $B'L'U'$ are, therefore, similar to $B'f'g'$ and $B'f'h'$ respectively; hence, $\frac{f'g'}{L'E'} = \frac{B'f'}{B'E'}$ and $\frac{f'h'}{L'U'} = \frac{B'f'}{B'U'}$,

which gives $\frac{f'g'}{f'h'} = \frac{L'E'}{L'U'} \times \frac{B'U'}{B'E'}$.

It is, generally, $L'E' = LE$

$$\times \frac{\text{constant of inversion between c. c. d. and c. v. d.}}{OL \times OE},$$

and similar relations for $L'U'$, $B'U'$, and $B'E'$; substitution shows that

$$\frac{L'E'}{L'U'} \times \frac{B'U'}{B'E'} = \frac{LE}{LU} \times \frac{BU}{BE};$$

but $\frac{LE}{LU} \times \frac{BU}{BE} = \frac{fg}{fh}$,

therefore, $\frac{fg}{fh} = \frac{f'g'}{f'h'} = S^2$.

It was found that

$$\tan \angle A'N'U' = 1/2 \tan \angle A'N'C',$$

i. e. U' is nearly equidistant from A' and C'; since $A'C'$ is ⊥ to $B'N'$ and far from the center of inversion the point U in the c. v. d. is nearly equidistant from A and C, and can be located by the eye. Usually, however, the no-load point C can be used instead of U; eq. (5) gives then the speed with the no-load speed as unity.

TORQUE

The torque in synchronous watts is

$$= \frac{\text{rotor output}}{S} = \frac{EG \times V}{S}.$$

The following approximate expression can also be used; it can be shown that S^2 is approximately equal to the efficiency of the rotor:[6]

$$S^2 = \sim \frac{EG}{EK} \text{ (Fig. 4)} \tag{5a}$$

Therefore, approximately:

$$\textit{Torque in synchronous watts} = \frac{EG \times V}{S}$$

$$= V\sqrt{EG \times EK}$$

$$= \sqrt{(\textit{rotor output})\,(\textit{rotor input})} \tag{6a}$$

It remains now to establish a few analytical relations useful for the construction of the locus from the test data. The branch $r_1 - x_1 - X$ of the circuit of Fig. 1 is equivalent to an impedance whose elements can conveniently be determined from the c. c. d. of Figs. 2 and 3 by observing that a point E' of coordinates u and v the equivalent resistance is

$$\frac{E'T'}{I'} = r_1 + \frac{v}{I'},$$

and the equivalent reactance

$$= \frac{R'K'}{I'} = x_1 + \frac{S'N' - u}{I'} = x_1 + X - u/I'.$$

Substituting for u and v their values as functions of $\sin a$, $\sin b$ etc. and denoting $1 + x_2/X$ by k (with $k = \sim 1$), it is found:

At the locked point L', $s = 1$:

Equivalent resistance $= r_1$

$$+ \frac{r_2}{k^2 + (r_2/X)^2} = \sim r_1 + r_2/k^2 \tag{7}$$

Equivalent reactance $= x_1$

$$+ \frac{X\,[r_2^2 + x_2\,(X + x_2)]}{r_2^2 + (X + x_2)^2}$$

$$= x_1 + \frac{x_2 + \frac{r_2^2}{(X+x_2)}}{k + \frac{r_2^2}{X\,(X + x_2)}} = \sim x_1 + x_2/k \tag{8}$$

At the no-load point C':

Equivalent resistance $= r_1 + \frac{r_2}{2\,k^2}$ (9)

Equivalent reactance $= x_1 + X - \frac{X^2}{2\,(X + x_2)}$

$$= x_1 + X\,\frac{2\,k - 1}{2\,k} \tag{10}$$

At the point A': (11)

Equivalent resistance $= r_1$

Equivalent reactance $= x_1 + X\,\frac{2\,k - 1}{2\,k}$ (12)

At the point B' ($s = \propto$);

Equivalent resistance $= r_1$ (13)

Equivalent reactance $= x_1 + X - \frac{X^2}{X + x_2}$

$$= x_1 + x_2/k \tag{14}$$

CONSTRUCTION OF THE DIAGRAM FROM TEST DATA

The necessary tests are: 1. Resistance r_1; 2. Locked point L: I_s amperes, W_s watts, $\cos \phi_s$ = power factor; 3. No-load point C: I_0 ampere, W_0 watts. The open rotor circuit point test should also be made, whenever possible (slip ring motors, repulsion-induction motors).[7] One of the difficulties of the problem is the fact that the point A is not given by the test; in the majority of methods of constructing the diagram

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[6] A. S. McAllister, "Simple Circle Diagram of the Single-Phase Induction Motor" *Electrical World*, June 30, 1906. See also Appendix 2.

[7] The no-load test point corresponds to a small friction torque; experience shows that a correction for this torque, theoretically simple, is not necessary.

A is considered as coinciding with C; when this is permissible, as in large motors, it greatly simplifies the construction; but in small motors the arc $A\,C$ is not always negligible, and it is necessary to find the point A, which involves certain complications.

The small chord $A\,C$, Fig. 2, is nearly ⊥ to the diameter $A\,O_2$ and (equation **4a**) nearly equal to

$$\frac{\text{rotor loss at } C}{V}\,;$$

moreover, with γ very small, $A\,C$ nearly coincides in direction with $O_3\,A$; therefore,

$$O_3\,C = \sim O_3\,A - \frac{\text{rotor loss at } C}{V} = \frac{V}{2\,r_1}$$

$$- I_0^2 \times \frac{r_2}{2\,k^2} \times \frac{1}{V}\,,$$

(equation **9**); equation (**7**) shows that

$$\frac{r_2}{k^2} = \frac{W_s}{I_s^2} - r_1;$$

with this value $O_3\,C$ can be calculated and O_3 located on $O\,Y$; the circle 3 of radius $\frac{V}{2\,r_1}$ is then drawn and determines the points O and A, the latter as the intersection of the circle 3 with $O_3\,C$ produced (or, more accurately, with the inverse of $A'\,C'$, *i. e.* with a circle passing through O and C and having its center on the line $O\,B_1$ ⊥ to $O\,Y$).

The next step is to calculate the angle γ; it is always so small that the following method is sufficiently accurate: x_1 and x_2 are calculated from equation (**8**) which gives: $x_1 + x_2/k = \sim (x_1 + x_2) = V/I_s \times \sin\phi_s$; it may be assumed that $x_1 = \sim 0.6$ to 0.7 of $(x_1 + x_2)$; X is calculated from equation (**10**) as follows:[8]

$$x_1 + X\,\frac{2\,k - 1}{2\,k} = \sim x_1 + X/2 = V/I_0\,;$$

equation (**7**) gives r_2/k^2 as above; with these data

$$\tan\gamma = \frac{r_2}{X + x_2} = r_2/k^2 \times \frac{X + x_2}{X^2}$$

can be calculated. The center O_3 of the locus is the intersection of the perpendicular bisector of $C\,L$ with a line passing through A and making an angle $90 - \gamma$ with $O_3\,A$. As a check, it will be found that the point A found above is either on the locus or at a negligible distance from it.

If the object of the test is the determination of the constants of the motor, more accurate values of $x_1 + x_2/k$ and X can be found from the diagram as follows: If $\phi\,\infty$ is the angle of lag at B, then equations (**13**) and (**14**) give:

$$x_1 + x_2/k = r_1\tan\phi\,\infty = r_1 \times \frac{O\,B_1}{B\,B_1} \qquad (15)$$

On the basis of equation (**11**) and (**12**) X is calculated from the equation

$$\left(x_1 + X\,\frac{2\,k - 1}{2\,k}\right)^2 + r_1^2 = \left(\frac{V}{O\,A}\right)^2 \qquad (16)$$

with k calculated with the previously found preliminary value of X.

If it is desired to calculate the rotor loss by the exact method (App. 1), the point N on the circle 3 can be located by observing that

$$O\,N = \frac{V}{\sqrt{r_1^2 + (X + x_1)^2}} = \sim \frac{V}{X + x_1}\,.$$

If O_3 is at an inconveniently great distance from the locus, the necessity of drawing the circle 3 can be avoided as follows: The angle β (Fig. 2) of the horizontal $A\,J$ with the tangent $A\,j$ to the circle 3 is given by

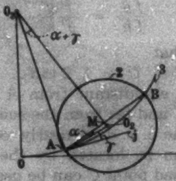

FIG. 6

$$\sin\beta = \frac{A\,J}{A\,O_3} = \sim \frac{2\,r_1\,I_0}{V}\,.$$

$A\,C$ is nearly ⊥ to the diameter $A\,O_2$, which makes an angle γ with $A\,j$, i. e. $A\,C$ makes an angle $= \sim \beta + \gamma$ with $O\,Y$; γ is calculated as shown above; the direction and length of

$$A\,C = \sim I_0^2\,\frac{r_2}{2\,k^2\,V}$$

determine the point A and the locus 2. It can easily be seen that

$$\angle\,J\,A\,O = \frac{\angle\,A\,O_3\,J}{2} = \beta/2,$$

i. e. the point O is the intersection of $O\,Y$ with the bisector of the angle $J_1\,A\,j$; this bisector can be drawn by the eye. Finally, the point B ($s = \infty$) is determined by the angle $O_3\,A\,B$ as follows: In Fig. 6 let R be the radius of the locus and $A\,j$ = the tangent to the circle 3; then,

$$\sin\angle\,A\,O_3\,M = \sin(\alpha + \gamma) = \frac{A\,M}{A\,O_3}$$

$$= \frac{R\cos\alpha \times 2\,r_1}{V}\,;$$

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[8] If the open rotor circuit test is available, it gives directly $x_1 + x = \sim \frac{V}{\text{current}}$ it may be observed, however, that this test, made with the rotor at rest, cannot be considered as giving the point N and used for the determination of the circle 3, because, unlike N, it does not correspond to the same conditions of the core loss and friction as the point C.

hence, developing,

$$\tan\alpha = \frac{2\, r_1 R}{V \cos\gamma} - \tan\gamma = \sim \frac{2\, r_1 R}{V} - \tan\gamma \quad (17)$$

Fig. 7 gives an example of the diagram applied to a 1/4-h. p., four-pole, 60-cycle motor. Resistance $r_1 = 6.8$ ohms; no-load test: 220 volts, 2.04 amperes, 116 watts; locked test: 220 volts, 8.46 amperes, 1300 watts. For this motor $\gamma = 3$ deg. 37 min., $\epsilon = 36$ deg. 33 min., $\theta = 3$ deg. 6 min. The coefficients in equations (2) and (3) are 0.998 and 1.011 respectively. Brake test points are shown in the diagram.

Appendix I

In Fig. 4A let 5 be a circle described on $B'N'$ as diameter. This circle is the voltage locus of a polyphase motor of exciting reactance X and of constants r_1, x_1, r_2, x_2;[9] it passes through L' because $\angle B' L' C' = \pi/2$. At a point E_1' the rotor current is $\frac{N' E_1'}{X}$, and the rotor loss

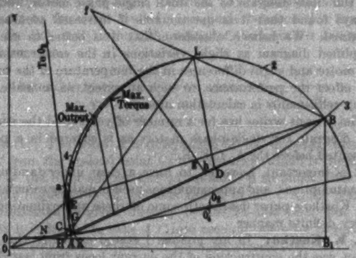

FIG. 7

$$= \frac{N' E_1'^2}{X^2} \times r_2 = \frac{N' B' \times N' K' \times r_2}{X^2}$$

$$= \frac{X^2 I'}{X + x_2} \times \frac{K' G' \times \cot\gamma \times r_2}{X^2} = K' G' \times I',$$

i. e. the same as for the single-phase motor at E'. The current locus corresponding to 5 is a circle 6 of center O_6 passing through N, L and B and normal to the circle 3 at N,[9] the points E_1 and E lie on the inverse of the line $E_1' E'$, i. e. on a circle 7 passing through O and having its center O_7 on $O\,T'$. Since E_1' and E' correspond to different voltages $O E_1'$ and $O E'$, the rotor losses in the c. v. d. are in the ratio

$$\left(\frac{O E_1'}{O E'}\right)^2 = \left(\frac{O E}{O E_1}\right)^2.$$

The polyphase motor rotor loss is proportional to $N E_1^2$, therefore, the single-phase motor loss is proportional to

$$N E_1^2 \times \left(\frac{O E}{O E_1}\right)^2,$$

and the coefficient of proportionality is found by reference to the point L where the loss is[9] $D_1 L \times V$ (with $D_1 L \perp$ to $N O_6$) which gives

$$\textit{Rotor copper loss} = O E^2 \times \left(\frac{N E_1}{O E_1}\right)^2 \times V \times \frac{D_1 L}{N L^2} \quad (4)$$

Appendix II

At a point E' (Fig. 3) of coordinates u and v, the rotor input $= E' K' \times I' = v \times I'$; the rotor output $= (E' K' - G' K')\, I' = (v - u \tan\gamma)\, I'$; rotor efficiency

$$= \frac{v - u \tan\gamma}{v}$$

$$= \frac{\sin a \times \cos a + \sin b \times \cos b - (\sin^2 a + \sin^2 b) \tan\gamma}{\sin a \times \cos a + \sin b \times \cos b};$$

substituting for sin a etc. their values and transforming, it is found:

$$\textit{Rotor efficiency} = (1 - s)^2 \times \frac{2\,s - s^2 - \tan^2\gamma}{2\,s - s^2 + \tan^2\gamma} \quad \textbf{(5b)}$$

If $\tan^2\gamma$ is small relative to $2\,s - s^2$, as at the point of maximum torque, then

$\textit{Rotor efficiency} = \sim (1 - s)^2 = \sim S^2.$

Discussion

V. Karapetoff: Mr. Kostko deserves much credit for having consistently followed what may be called a graphico-analytical method of solution of the single-phase induction motor, without the use of complex quantities. He is somewhat in the position of an arctic explorer who went to verify indefinite rumors about a favorable passage, and proved concisely that there was none. Someone had to do it, but few will appreciate the real value of a contribution consisting of a negative result. To me Mr. Kostko has proved only that by the method which he adopted no particularly useful results can be obtained either for a designer, an operating man, an experimenter, or a theoretical investigator. In order to use his results intelligently, one has to study carefully about twelve columns of weary mathematics and several complicated geometric figures. And when one finally arrives at the end, one finds the familiar old fact that the no-load and short-circuit tests alone do not determine the circular locus. It is necessary to use approximate relationships and empirical coefficients as given in his paper.[1] The limits of validity of these assumptions, or the magnitude of error committed, would be difficult to estimate, especially with a new motor of unusual constants.

To me the present situation and the possible future progress in the quantitative theory of the single-phase induction motor seem to be as follows:

(*a*) *The "one variable" diagram.* The difficulty with either the rotating-field or the cross-field theory of the single-phase induction motor is that both lead to equivalent diagrams with two variable branches. Thus, in Mr. Kostko's Fig. 1 one branch has the variable quantity $r_2/2\,s$, and the other has $r_2/2\,(2 - s)$, where s is the variable slip. It has been shown some time ago that the single-phase motor may be replaced by an equivalent diagram with one variable branch only (see V. Karapetoff, JOURNAL of the A. I. E. E., Vol 40, 1921, Aug., p. 641. Fig. 3). This diagram admits of a much simpler analytical or graphical treatment than either of the two usual diagrams, and should be used in the future.

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[9] See JOURNAL A. I. E. E., April, 1921, pp. 326-332.

[1] A. I. E. E. JOURNAL Jan. 1922, p. 35, first column.

(b) *The circular locus.* In the "one variable" diagram mentioned above, the admittance of the variable branch is $s\,(2-s)\,Y_e$, where s is the slip and Y_e is a constant admittance which characterizes a given motor. Thus, the locus of the variable admittance is a straight line in the direction of the vector Y_e. A constant admittance, $(X + Z + r)^{-1}$, is added in parallel to this admittance, still leaving the straight-line locus. The first inversion gives a circular locus for the equivalent impedance. Two more inversions are necessary to account for the remaining constant parts of the circuit, but the inverse of a circle is also a circle so that the final result is a circular locus. This is the simplest exact proof of the circular locus of the single-phase induction motor that I know of. No complicated analytical or graphical proof is necessary.

I have shown on another occasion that it is not necessary to change the circle at each successive inversion, but that the first circle and the last circle can be made to coincide by properly changing the scale (See Sibley *Journal of Eng'g* Vol. 32, 1921, p. 42). Therefore, for a single-phase induction motor of given constants it is now possible to construct a circle diagram of a current, with hardly any computations, except for measuring a few lengths and taking their reciprocals. This diagram also inherently contains slip values. Knowing the primary current, its phase angle, and the corresponding slip, it is not difficult to compute the remaining characteristics.

(c) *The analytical method.* The same new equivalent diagram, mentioned above, leads to the following expression for the equivalent impedance of a single-phase induction motor:

$$Z_{eq} = Z_1 + \left[Y + \left\{ \mathbf{X} + \left[(X + Z + r)^{-1} + Y_e\, s\,(2-s) \right]^{-1} \right\}^{-1} \right] \qquad (1)$$

In this formula all the quantities are motor constants, expressed as complex numbers, and the only variable is the slips s. By giving different values to s, the values of Z_{eq} can be computed, and the corresponding values of current vector found by dividing the applied voltage by Z_{eq}. It is true that at the present time numerical computations with complex quantities are somewhat tedious, but then one has the advantage of using a formula which contains only standard operations of addition of impedance in series and admittances in parallel. One does not have to study a complicated analytical theory with special vector diagrams, several angles, simplifying assumptions, etc.

Formula (1) probably represents the simplest analytical expression for the motor in question, since it corresponds to a diagram with but one variable branch. Our next problem is not so much to simplify this expression as to devise a simpler method of computing complex quantities. At the present time the most convenient method seems to be to use the trigonometric or exponential form for multiplication, division, and reciprocals; and to use the orthogonal form for addition and subtraction. The writer has constructed a chart and a device (vectrometer) by means of which changes from one form to the other takes less time. The final solution of the difficulty should be a computing machine made to add and to multiply complex quantities directly. Such a machine would be very useful in many computations relating to a-c. machinery and circuits.

(d) *The circular locus from a test.* It is a well known fact that the no-load and short-circuit tests alone are not sufficient to determine the circular locus of either a polyphase or a single-phase induction motor, since a circle has to be determined by three points. In large and medium-size polyphase induction motors of usual proportions the center of the circle usually lies on a certain horizontal line determined by the no-load losses, but for small single-phase motors this assumption is not permissible (See for example, Mr. Kostko's Fig. 7).

The tangent from the origin to the circle determines the point at which the power factor is a maximum and this may be a convenient additional datum to make the circle definite. I know from experience that this method works well on a small polyphase motor. To obtain this value, a reliable power-factor meter is connected in the motor circuit and watched while the motor is coming up to speed, or while it is being loaded. It is easy then to read the maximum value which the power factor reaches. The speed or the slip may also be read at the same time. This test gives the direction of the tangent from the origin to the circle, and together with the no-load and short-circuit point determines the circle itself, and the ampere-speed characteristic.

If a power factor meter is not available, a wattmeter may be used and read at its maximum indication, as the machine is loaded. This will give the horizontal tangent to the circle, and thus furnish the necessary additional information for drawing the circle itself.

J. L. Hamilton: Mr. Kostko attempts to get a little more accurate analysis of the single-phase induction motor. It is doubtful if there is any electrical problem more difficult of solution than this one.

The "Tilted Diagram" gives slightly more accurate results on very small single-phase motor of one-half h. p. and smaller. For larger size motors the accuracy is not improved very much, by using the diagram.

The present writer has used a number of refinements in applying the circle diagram to the small single-phase motor, and has always found that it is questionable if increased accuracy is obtained. We believe, therefore, that it is better to use the simplified diagram as slight variations in the construction of the motor and slight differences in the temperature of the motor will effect the performance, to such an extent as to make too many refinements in calculation useless.

The present writer has for a number of years used the simplified diagram for single-phase motors as is covered in a paper presented before the A. I. E. E.[2]

It is important, however, to have a clear understanding of the assumptions, and approximations used in making calculation. Mr. Kostko's paper deals with some of these approximations in a very definite manner.

J. K. Kostko: In my preface I stated explicitly that my object was the construction of the current locus from test data. Prof. Karapetoff's note deals almost exclusively with a question which is entirely outside of the scope of the paper—the construction of the diagram and the predetermination of the performance from the design data of the motor. My paper is mentioned only in the first paragraph, and the mention consists of a number of statements of such general nature that, unfounded as they are, it would be a hopeless task to try to refute them in their present form, especially in the short time given to me for reply. For certain reasons I must abandon the attempt to obtain some light on the meaning of these statements, and confine myself to a short discussion of the only definite statement, which is, apparently, the key to the rest of Prof. Karapetoff's criticism. I refer to the statement: "one finds the familiar old fact that the no-load and short-circuit tests alone do not determine the circular locus."

The fact is, indeed, old and familiar—and has nothing to do with the method of the paper, which is based on three tests, not on two, as clearly stated in the paper.

The problem of constructing the circle diagram from the no-load and locked tests alone has been completely solved in the classical works on this subject; they show the necessity of certain simplifying assumptions and prove the futility of all methods such as the one imputed to me by Prof. Karapetoff, *i. e.,* where it is sought to make further progress without additional physical data. Prof. Karapetoff suggests that these data be obtained from certain tests involving the use of mechanical power; but this drastic remedy, which would greatly impair the practical value of the circle diagram, is entirely unnecessary, because by the method of the paper the accuracy can be extended beyond the most exacting requirements of practical work without the complication of unusual and difficult tests. In this method I take advantage of the fact that, while we speak of the no-load and locked tests alone, we always make one more test: We measure the primary resistance r_1, without which the circle is of no value for the applications; I use this resistance not only for the study of the performance, but for the construction of the diagram itself, by proving that the current circle is in a simple angular relation to another circle, of radius determined by the primary resistance alone (circle 3 of the paper, of radius $V/2\,r_1$). The principle is quite general; I found it applicable to many types of machines; its advantages are very well illustrated in the case of a polyphase motor[3], where the circle of radius $V/2\,r_1$ is determined in magnitude and in position, and is normal to the current locus; by this condition the latter is completely determined without any simplifying assumptions or additional tests. The diagram of the single-phase motor is not so simple; but even in this case the results are far more accurate than with the two tests only, as follows from the following considerations:

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[2] A. I. E. E. TRANS., Vol. XXXIV, 1915, Part II, p. 2443.

The inherent errors of the method are (1) the exact location of the point A (which determines the position of the circle 3) is not known; (2) the angle of tilt $\beta + \gamma$ can be determined only approximately; β = angle between the horizontal and the tangent to the circle 3 at A; γ = angle between this tangent and the line $A\,O_2$ through the center of the locus; it can easily be seen that

$$\tan \beta/2 = \frac{r_1}{X\dfrac{2\,\kappa - 1}{2\,\kappa} + x_1}, \quad \tan \gamma = \frac{r_2}{X + x_2}.$$

As to (1): The point A is determined by its (directed) distance $A\,C$ from the no-load point C; this distance (which is the measure of the rotor copper loss at no-load) is so small, that it is simply neglected in all methods known to me, *i. e.*, the point A is considered as given directly by the no-load test; but even when it is desired to take $A\,C$ into account, the error committed on it is very small (= error of the approximate formula 7 of the paper), so that the point A can be located without an appreciable error, thus accurately determining the circle 3, its tangent at A and the angle β; in other words, the introduction of the circle of radius $V/2\,r_1$ practically eliminates the error of the tilt due to the primary resistance and reduces the error of the method substantially to that committed on the small angle γ. In small motors γ is usually of the order of magnitude of 1/3 to 1/4 of the total angle of tilt, so that the error of the method can be described as a small error committed on a fraction of a small quantity.

Taking, for instance, such abnormal values as 20 per cent error on γ and 15 to 20 degrees angle of tilt, the error is of the order of one degree; it is certainly not greater than the error due to the unavoidable assumptions, such as non-saturated magnetic circuit and sine wave currents.

A numerical estimate of this error would be very difficult; but a graphical study of any individual case can very simply be made as follows: With the constants of the motor (either given or approximately determined from the diagram) the exact diagram is drawn by any of the numerous available methods;[4] then, assuming that only the primary resistance the no-load and locked points C and L are known another diagram is drawn by the method of the paper; the comparison of the two diagrams shows at a glance the order of magnitude of the error due to the method itself, *i. e.*, excluding the influence of errors common to all diagrams such as saturation, etc. In Fig. A this comparison is made for a 1/20 h. p. motor whose constants are derived from the diagram of Fig. B constructed from test data; the numbers with accents refer to the exact diagram. As seen even in such a small motor the error of the method has no appreciable influence on the diagram within its working range, where both circles practically coincide. No additional test could give better results.

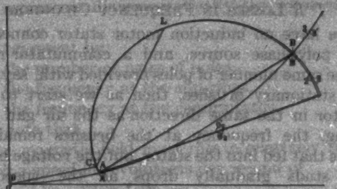

FIG. A

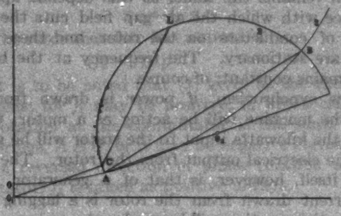

FIG. B

I agree with Mr. Hamilton that there is little advantage in the use of the exact diagram above 1/2 h. p. (4 pole). The use of the tilted diagram can be facilitated by a gradual extension of simplifying assumptions as follows: (1) exact diagram; (2) point A coincides with the no-load point; (3) same as (2) and negligible rotor resistance, angle $\gamma = 0$; (4) same as (3) and negligible stator resistance, *i. e.* non-tilted diagram.

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[3] Journal A. I. E. E., April 1921, p. 326.

The circle of radius $V/2\,r_1$, is a familiar feature in the theory of synchronous motors (circle of zero power).

[4] For instance, the admittances of the points A, C, L and B can be calculated from the impedances given by the (exact) formulaes (7) to (14) of the paper; these admittances determine the points A, C, L and B, *i. e.*, the circle as well as the power lines $C\,L$ and $A\,B$.

Polyphase Commutator Machines

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In a certain type of frequency-changer which consists of an armature similar to that of a synchronous converter, viz., a type of direct-current armature with slip rings on one side and a commutator on the other, the energy loss due to the currents flowing in these conductors is here analyzed.

The energy loss appearing as heat depends upon the degree to which the currents which flow in or out at the commutator end or the slip rings compensate one another. In the case of the synchronous converter the former are direct currents while the latter are alternating currents.

In the case of the frequency-changer, they are alternating currents of different frequency.

This paper analyzes the losses taking account of the time and space overlapping of the currents and gives the results for different numbers of phases and for different power factors.

$I^2 R$ Losses in Frequency-Changers

If we have an induction motor stator connected to a polyphase source, and a commutator rotor of the same number of poles provided with, say, three-phase stationary brushes, then as we start to rotate the rotor in the same direction as the air gap field is rotating, the frequency at the brushes remains the same as that fed into the stator, but the voltage between brush studs gradually drops as the speed rises towards synchronism. Upon passing through synchronism the voltages reverse; but the direction of phase rotation remains the same, as this depends upon the sequence with which the air gap field cuts the phase bands of conductors on the rotor, and these phase bands are stationary. The frequency at the brushes also remains constant, of course.

Below synchronism, if power is drawn from the rotor the machine will be acting as a motor; that is to say the kilowatts input to the stator will be greater than the electrical output from the rotor. The rotor action itself, however, is that of a generator, and if the current drawn from the rotor is a lagging one, a demagnetizing action will be produced.

After passing through synchronism mechanical power will have to be put into the shaft when power is withdrawn from the rotor and then power will be simultaneously delivered by the stator. The relative direction of motion of any one rotor conductor and the field will have become reversed and consequently also the direction of generator current in such conductor; but the direction of the field relatively to any one phase band of rotor conductors remain as before; hence a lagging current in the circuit supplied by the rotor, which previously produced a demagnetizing action, now produces a magnetizing one, and we have so far as the rotor alone is concerned an a-c. generator whose voltage increases upon an inductive load and drops upon a capacity load. The corresponding case without a-c. excitation of the stator, would be that of a salient pole stator with the commutator brushes rotating in a direction opposite to that of the rotor. Such a generator ought to self excite when connected to an inductance; or if excited by direct current on the stator, would have a negative regulation upon an inductive load.

Coming back to the first case and making the number of conductors the same on the Δ-connected stator and rotor, as also the coil throw, but the direction of coil progression different, we have a curious combination, when this machine is driven at twice synchronous speed. If, say, an a-c. supply be connected to the stator only, a magnetizing current will be drawn from the supply, having the usual 90 deg. lag. If instead, the rotor be connected to this supply, the same amperes of magnetizing current will be drawn, but the current will be leading by 90 deg. Consequently, if both stator and rotor be connected in parallel to the supply, the magnetizing current can circulate between the stator and the rotor without any being supplied from the outside system. To obtain this circulation of magnetizing current, the small voltage required for $I R$ and leakage reactance purposes must be obtained; the former would be immediately provided by a slight shift of the brushes, causing the phase bands on the rotor to be slightly displaced from those on the stator. In this case the voltage of the machine, being controlled by the excitation current circulating between stator and rotor, would be adjusted by slight movements of the brush ring backwards or forwards. In such a machine the field rotates in the same direction as the rotor at half the speed of the rotor and consequently a rotor conductor is cutting the field in a direction opposite to that in which the stator conductor, immediately opposed to it, cuts the field, the two speeds of cutting being the same. Hence we have in the case of such a machine acting as a generator, complete compensation of the stator ampere conductors by the rotor ampere conductors immediately opposite to them. Such a machine should prove self-regulating.

In addition to the $I R$ voltage required to circulate the magnetizing current, there will be required on account of the slight magnetic leakage of stator and rotor conductors, a small component voltage in the same phase direction as that of the voltage produced by the air gap field—in phase for the rotor, out of phase for the stator. If this were not taken care of, the

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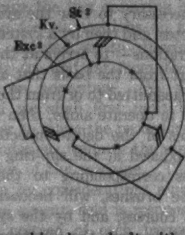
load current would divide unequally between stator and rotor. Probably a small a-c. excitation of variable voltage and field phase, will have to be inserted, the line terminals being located at centers of phases of exciter windings.



The type of machine here dealt with is that in which a commutator and set of slip-rings are connected to a common winding, the rotor thus being similar to that of a synchronous converter.

In the case of a synchronous converter, a field structure with separate excitation windings is used, but it would be possible to produce the requisite magnetizing force by alternating currents introduced at the slip-rings, or by direct current at the commutator. In fact converters have been proposed in which the whole mechanical structure remains at rest except the system of brushes which plays upon the commutator. In this case the magnetic field rotates in space synchronously with the brushes, and the external structure has neither salient poles nor windings but serves merely to close the magnetic circuit of the rotor. Although both elements, corresponding to the stator and rotor of the synchronous converter, remain at rest here, it is still necessary to employ a considerable air gap in view of the fact that the distribution of three-phase or six-phase currents in the armature winding, while nearly cancelling the distribution of direct currents over each pole pitch, do so only *on the average*, leaving relatively large uncompensated positive or negative ampere turns of armature reaction locally, which fluctuate both in time and in position relatively to the tap points and to the brushes. This feature which similarly becomes objectionable in the frequency changer discussed below, can be mitigated by chording the winding.

Now if in the above type of machine, the brushes should be rotated at a speed other than that at which the air gap field rotates, alternating current would clearly be drawn from the machine instead of direct current, and the frequency of the commutator current would correspond to the speed difference. Further, should three sets of brushes per pair of poles be evenly disposed upon the commutator instead of two, three-phase currents would be withdrawn. For mechanical convenience we may evidently bring the brushes to rest, maintaining the same relative velocities by rotating the remainder of the structure, or by rotating the wound armature only. We then have the frequency changer about to be discussed here. The proper chording of the coils to minimize the irregularities of resultant armature reaction has been specified by Lamme[1] to be approximately half the angle between consecutive brushes on the commutator; for instance, if we had six brushes on a two pole commutator the coil span would be made 150 deg. or 210 deg. instead of 180 deg.

Before considering the I^2R losses in this machine it will be well to obtain a clear picture of the conditions arising by noting a few salient features.

Fig. 1 represents diagrammatically the rotor of the machine.

Let us represent by

p the number of pairs of poles.

f_1 the frequency at the slip-rings.

f_2 the frequency at the commutator.

Then we note that

1. The magnetic field must rotate relatively to the rotor with a speed in revolutions per second of

$$n_1 = f_1/p$$

2. It must rotate in space, or relatively to the brushes on the commutator, with a speed of

$$n_2 = f_2/p$$

3. The rotor therefore has a speed of

$$(f_2 - f_1)/p$$

4. It is to be noted that (3) gives us the choice of two speeds; for f_2 may be positive, in which case the phase rotation at the commutator is the same as at the slip-rings, *A B C*, or it may be negative corresponding to a reversed direction of phase rotation on the commutator; f_1 is taken as positive always.

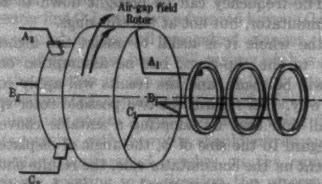


Fig. 1

5. The direction of rotation of the rotor is the same as that of the field relatively to the stator, if f_2 is greater than f_1, or if f_2 has any negative value. It is the reverse of the direction of rotation of the field relatively to the stator if f_2 is positive and less than f_1.

6. The generated voltage of the first frequency, measured from one slip-ring tap point to the next, corresponds directly to the number of armature

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[1] U. S. Patent No. 1318775, 1919.

conductors, the field strength, and the relative speed of field and conductors, or to f_1/p.

7. The generated voltage of the second frequency, measured between consecutive brushes on the commutator, corresponds similarly to the number of conductors, the field strength and the *same* velocity.

8. Thus if we have the armature tapped for six phase slip-rings, and brushes on the commutator for six phases also, the generated voltage of frequency f_1, between slip-rings connected to consecutive taps, will be the same as that of frequency f_2 between consecutive brushes; the currents also will be equal, barring magnetizing current and a small component which provides part of the power lost in the conversion.

9. The commutator frequency f_2 may be either higher or lower than the slip-ring frequency f_1. But if one of the two frequencies is to be a very low one, it is advisable to adopt the lower for the commutator, and this becomes essential if the lower frequency is to be subject to variation passing through zero, that is, changing its direction of phase rotation. In deciding which frequency to assign to the commutator, it will be noted that:

a. The mechanical speed is the same in either case.

b. The core loss is not greatly affected by the choice, since the field rotates at a speed corresponding to the one frequency, relatively to the stator, and the other frequency relatively to the rotor.

c. The relative speed of *rotor* and field should be high, for minimum size of machine; *i. e.*, the slip-ring frequency should be high.

d. With reference to commutation, the transformer action in the coils connected to the segments under the brush will be the smaller the lower is the frequency on the commutator side.

e. The frequency can be brought down to zero at the commutator, but not at the slip-rings.

On the whole it is usual to assign the higher frequency to the slip-rings, but no assumption on this point will be made, and the results will apply equally either way. As regards the two possible rotor speeds, we shall find that by adopting a suitable convention with regard to the sine of ϕ, the angle of displacement of current on the commutator side, the results obtained apply equally for either speed, *i. e.*, for f_2 positive or negative.

Now the currents in the rotor will result from the combination of the slip-ring currents at frequency f_1, and the commutator currents at frequency f_2.

Generally, in the case of superposed currents of two frequencies, the determination of the mean I^2R loss averaged over a few cycles, is simple, as each set of currents involves its own loss, and the net resultant loss is merely the sum of the two separate ones, irrespective of their relative magnitude or phase. In the present case, these simple relations do not hold, for although in any one conductor we have merely current of the first frequency introduced via the slip-rings, and for brief periods, we similarly have the actual current of the second frequency superposed in the same conductor, yet before one cycle is complete, the relative movement of commutator and brush has transferred this conductor into another phase group of the f_2 system.

It becomes necessary to view the cycle of events for atypical conductor, and then by a system of averages— or simple integrations— to arrive at the resultant loss.

We may start from the basis that should power be mechanically transmitted to or from the rotor, enabling the one system to operate alone, then the distribution among the arms of the delta-connected rotor of the Y-currents introduced at the slip-ring taps, or at the equivalent taps corresponding to the instantaneous positions of the brushes, will necessarily follow the ordinary $Y-\Delta$ courses; and by the symmetry of the system, the voltage upon the idle taps or brushes, as the case may be, will form a symmetrical three-phase or six-phase system. As this applies to the case of operation with power being supplied either via the commutator or via the slip-rings, the result of superposing the two will leave balanced conditions and we may therefore consider that each set of currents upon entering the rotor divides up among the delta arms in the orthodox way, so that at any instant the actual current in any conductor is the sum of the two corresponding instantaneous currents. The same reasoning may, of course, be applied to other numbers of phases than three or six on either or both sides.

We now require a simple way of viewing the life history of a typical conductor, determining for any one instantaneous value of the f_1 current the range of values of the f_2 current. We can most readily do this by reference to the only feature which is common to the two frequencies, viz.: the armature reaction. To render this process more clear, we shall on paper bring the air-gap field to rest in space by rotating the brushes on the commutator, and by readjusting the rotor speed suitably.

Assume the field to be rotating clockwise, viewed from a given side of the machine. Superpose upon the whole machine a counter clockwise rotation of f_1/p revolutions per second, thus bringing the field to rest in space while the brushes rotate counter-clockwise at this speed. Note that f_2 may be negative.

We can now readily picture the current distribution in the rotor, since the armature reaction of the f_1 currents, and again that of the f_2 currents, will be represented each by a diagram fixed in space (although slightly pulsating or varying). Although produced by currents of different frequencies, these two diagrams will have the same number of poles, and on the average will cancel one another, the one being, at every instant, nearly superposable upon the reverse of the other— if for the moment we ignore the magnetizing current.

We have two methods open to us of investigating the I^2R loss; we may do so (1) by considering the loss occurring, from moment to moment, in the succession of conductors which occupy a point fixed in space, upon the rotor periphery; then averaging this up with respect to time, and again with respect to angular position.

Or (2) we may consider a marked conductor upon the rotor; average the loss occurring in it; and again average this up for all positions on the rotor. This latter method enables us to discriminate between conductors near to, and far from the slip-ring taps, and thus has an advantage. We shall adopt this procedure, and we shall first omit the magnetizing current, in order to make the procedure more clear.

With this omission, we have the same power factor on the two sides of the machine. That this must be so, can be seen by considerations along the following lines: The same air-gap field is responsible for causing the generated voltage of each frequency, and it is stationary in space. The armature reaction diagram of the currents of frequency f_1 must be generally similar to that of the currents of frequency f_2, except for sign since the sum of the two produces the working field and we are neglecting the magnetizing current for the present. But the armature reaction of the watt component of current of either frequency has its polar center lines at right angles to those of the air gap field. Therefore, these two component armature reactions, for the two frequencies, have their polar center lines coincident; the watt component of current of frequency f_1 must be equal to the watt component of current of frequency f_2, in order to effect balance of mechanical torque; and therefore the armature reactions of these two watt components balance one another; hence the armature reactions of the two remaining components must balance one another, *i. e.*, the two wattless current components must be equal and therefore the power factor must be the same on the two sides.

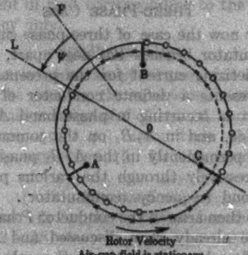


Fig. 2

We shall now show, still neglecting the magnetizing currents, that for positive values of f_2 not only is the power factor the same on the two sides, but the sine of ϕ, which determine whether the current is leading or lagging, is the same; while for negative values of f_2 the power factor is the same on the two sides, but a lagging current on the slip ring side is associated with a leading one on the commutator side, and vice versa.

Fig. 2 indicates diagrammatically a two-pole rotor tapped at $A\ B\ C$ for three-phase slip rings; the line $O\ F$ represents the stationary polar center line. Assume the rotor to be driven in a counter-clockwise direction mechanically and to be acting as an a-c. generator, then the current in every conductor of the $A\ B$ phase band will reach its maximum when the center line $O\ L$ of the phase band has some definite angular position, say ψ in advance of $O\ F$, where ψ may be positive or negative. If the load be noninductive ψ will be zero and the current will be a maximum in all conductors of the phase band at the moment when $O\ L$ coincides with $O\ F$. If the load be inductive and the current be lagging by an angle α, then when the current reaches its maximum in the conductors of the $A\ B$ phase band, the center line $O\ L$ will have advanced beyond $O\ F$ by the angle α, and in the well recognized manner, the conductors of the phase band will occupy such a position that the reaction of the currents in them has a component along $O\ F$ opposing the main field.

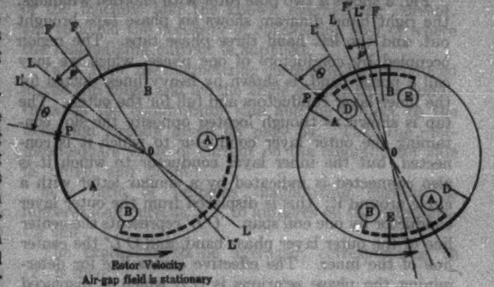


Fig. 3

If now the points $A\ B\ C$, instead of being fixed tap points rotating with the rotor, should correspond to the momentary positions of brushes on the commutator which are rotating in a direction the reverse of that of the rotor, then the movement of the center line $O\ L$ by the angle α will be in a clockwise direction in the figure. But as the voltage induced in the conductor is due to the motion of the conductor, and not that of $O\ L$, it will remain in the same direction as before, and hence also the current in the conductor if the machine is still acting as a generator via $A\ B\ C$. In this case, therefore, a lagging current will produce a reaction having a component along $O\ F$, tending to *increase* the field strength although the machine is acting as a generator and not a motor.

Hence we have the condition already outlined for the relative phase displacement on the two sides, *viz.*, that when f_2 is positive $\phi_1 = \phi_2$, but when f_2 is negative $\phi_1 = -\phi_2$.

We have seen that the power factor is the same on each side of the machine; it follows that the amperes per slip ring equal the amperes per brush stud, assuming the same number of phases each side, for the voltage between rings equals that between brush studs.

Fig. 3 shows a two pole rotor with chorded windings; the right hand diagram shows six phase taps brought out, and the left hand three phase taps. The region occupied by conductors of one phase, which we may call a phase band, is shown by heavy lines, dotted for the inner layer conductors and full for the outer. The tap is shown as though located opposite the slot containing the outer layer conductor to which it is connected, but the inner layer conductor to which it is also connected is indicated by a similar letter with a circle around it; this is displaced from the outer layer conductor by one coil span. $O\,L'$ represents the center line of the outer layer phase band, and $O\,L''$ the center line of the inner. The effective center line for determining the phase relations is $O\,L$ which is displaced from $O\,L'$ by half the angle of chording. It will be understood that the tap points shown may be either actual fixed taps connected to slip rings, or may represent the momentary position of brushes on the commutator; in either case the voltage generated in the phase band is the same, being produced by the movement of the conductors in the field and not by the movement of the center line of the phase band. If we are dealing with a commutator phase band the center line $O\,L$ may be rotating oppositely to the rotation of the rotor itself; *viz.*, when f_2 has a negative value.

In the figure, $O\,F$ represents the polar center line of the main field and ψ the angle, measured counter clockwise, of $O\,L$ from $O\,F$. We take the component of current in the phase band which has frequency f, to have a root-mean-square value of unity and we define its phase angle as follows:

If f is positive, $+\phi$ represents the angle by which the current *leads* with respect to conditions for unity power factor.

If f is negative, $+\phi$ represents the angle by which the current *lags* with respect to conditions for unity power factor.

In either case the power factor is $\cos\phi$ and a magnetizing armature reaction is associated with generator conditions when ϕ is positive.

It will be found that with this definition the current component of frequency f in every conductor of the phase band $A\,B$ is represented by

$$\pm\sqrt{2}\cos(\psi + \phi) \qquad (1)$$

for either direction of rotation of $O\,L$. Note that ψ is always to be measured in a counter-clockwise direction.

When we are dealing with a specific conductor P in say the outer layer, it becomes convenient to specify this by its co-ordinate measured from the center line of its phase band in the layer in question, or $O\,L'$ for the outer layer, instead of from $O\,L$, and consequently it becomes convenient to deal with the angular co-ordinate of $O\,L'$, rather than $O\,L$, with respect to the fixed field axes. It will be noted that we may still use expression (1), and define ψ therein as the angle measured counter clockwise from some suitable zero line $O\,F'$ fixed in space, to the phase band center line $O\,L'$; further the datum line $O\,F'$ will be the same whether $O\,L'$ is a center line of a slip ring phase band and therefore is fixed in the rotor, or whether it represents the momentary position of the center line of a commutator phase band and is rotating in the same direction as the rotor or the reverse. In other words, the chording angle does not enter into consideration in dealing with the difference of phase of the currents of the two frequencies in a conductor, either for positive or negative values of f_2.

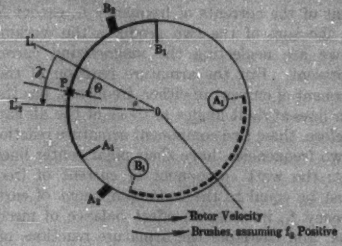


FIG. 4

THREE-PHASE CASE

Consider now the case of three-phase slip ring taps and commutator brushes 120 deg. apart, Fig. 4, and omit magnetizing current for the present. P in the figure represents a definite conductor of the rotor; it is shown as occurring in phase band $A_1\,B_1$ of the slip ring side, and in $A_2\,B_2$ on the commutator side. It remains permanently in the $A_1\,B_1$ phase band, but passes successively through the various phase bands of the second frequency (commutator).

Currents then arise in the conductor P having values which have already been discussed and represented by (1). They have respectively the values:

$$\sqrt{2}\cos(\psi_1 + \phi) \qquad \text{of frequency } f_1$$

$$\text{and} \qquad \sqrt{2}\cos(\pi + \psi_2 + \phi) \qquad \text{of frequency } f_2$$

The difference $(\psi_2 - \psi_1)$ may clearly have any value between $\pi/3 + \theta$ and $-\pi/3 + \theta$. Further, every value within this range is an equally probable one and will occur for the same number of seconds per hour of operation, on the average. We therefore require the average value of

$$2\,[\cos\psi - \cos(\psi + \gamma)]^2 \qquad (2)$$

for all values of γ within the range $(\theta \pm \pi/3)$, giving equal weight to each value. We shall next require the average value of this result for all values of ψ over a range of 2π. This will give us the loss in a specific conductor; to obtain the entire rotor loss we shall have to again average for all possible values of θ, *i. e.*, between $\pm\pi/3$ in our present three-phase case.

For the loss in conductor P we have therefore:

$$\frac{3}{2\pi^2}\int_{\gamma_1}^{\gamma_2} d\gamma \int_0^{2\pi} [\cos\psi - \cos(\psi+\gamma)]^2\, d\psi$$

where

$$\gamma_2 = \theta + \pi/3$$
$$\gamma_1 = \theta - \pi/3$$

which is equal to

$$3/\pi \int_{\gamma_1}^{\gamma_2} d\gamma\,(1-\cos\gamma) \qquad (4)$$

or to

$$2 - 1.653\cos\theta \qquad (5)$$

If we had current of the one frequency only in the conductor, the corresponding loss would be unity, as we have taken the current to have an r. m. s. value of unity. Hence the loss, in terms of that due to current of one frequency only, is given by the above expression (5). This is clearly least for the mid conductor of the phase band, *i. e.* for $\theta = 0$ while it is a maximum for the two tap conductors for which $\theta = \pm\pi/3$. For these two positions the relative losses are, respectively:

Mid conductor	34.7 per cent
Tap conductors	117 per cent

Finally, averaging expression (5) for values of θ over its range $\pm\pi/3$ we have for the relative total rotor loss

$$2 - 1.367 \qquad (6)$$

or 63 per cent of that corresponding to the current of one frequency only.

SIX-PHASE CASE

In the case in which six-phase provision is made on each side of the machine, the expressions become slightly modified to suit a range of θ of $\pm\pi/6$, and a range of the difference $(\psi_2 - \psi_1)$ amounting to $\theta \pm \pi/6$. Consequently expression (5) for the conductor loss becomes

$$2 - 6/\pi\cos\theta \qquad (7)$$

and expression (6) for the rotor loss becomes

$$2 - 18/\pi^2 \quad \text{or} \quad 0.176$$

so that the losses, in terms of those corresponding to the current of one frequency only, amount to

For mid conductor of phase band (min.)	9 per cent
For tap conductor (max.)............	35 per cent
For whole rotor..................	17.6 per cent

LOSSES ALLOWING FOR MAGNETIZING CURRENT

We may have the magnetizing current introduced at the slip rings or at the commutator, or partly at each; and either side may be the motor side. As a matter of fact we may arbitrarily say at which side we consider the magnetizing current to be introduced, as this affects only our definition of load current in which we already have a variable phase angle ϕ at our disposal. The case will therefore remain general if we consider the magnetizing current to be introduced at the slip rings and define the load current as being the current at the commutator side, no matter at which side power enters the machine, nor which of the two currents is the greater. We later give expressions enabling the loss to be written down in terms of the current on each side of the machine and the known magnetizing current, and so avoid the necessity of considering how or where the magnetizing current is supplied.

Take, then, the magnetizing current to be introduced at the slip rings, and let the angle ϕ refer to the conditions on the commutator side and be subject to the definition already given on page 54. Take the root-mean-square value of current on the commutator side as unity, and define:

m = ratio of amperes magnetizing current to amperes load current, *i. e.* to amperes on the commutator side.

The expression to be averaged, corresponding to (2), is then:

$$2\,[\cos(\psi_1+\phi) + m\cos(\psi_1 \pm \pi/2) - \cos(\psi_2+\phi)]^2 \qquad (8)$$

where the upper sign is to be taken if the slip ring side is the motor side, and the lower if the generator side. Or, we may average:

$$2\,[\cos\psi \pm m\sin(\psi-\phi) - \cos(\psi+\gamma)]^2$$

between limits zero and 2π as regards ψ and the limits for γ already used for three-phase and six-phase respectively.

The result is easily found to be:

$$[m^2 + 2a] + \text{Average value over the } \gamma \text{ range of}$$
$$2\,[b\sin\gamma - a\cos\gamma] \qquad (9)$$

where

$$b = \pm m\,.\cos\phi$$

$$a = 1 \pm m\,.\sin\phi$$

the signs being subject to the conditions stated above in connection with (8).

For the three-phase case the limits for γ are $\theta \pm \pi/3$ and the relative conductor loss becomes:

$$[m^2 + 2a] + 1.655\,[b\sin\theta - a\cos\theta] \qquad (10)$$

while for six-phase, γ varies between $\theta \pm \pi/6$ and the relative conductor loss becomes:

$$[m^2 + 2a] + 1.91\,[b\sin\theta - a\cos\theta] \qquad (11)$$

Now a may be taken as positive except when the magnetizing current exceeds the load current being considered; and b may be positive or negative; the maximum value of (10) will therefore occur for $\theta = \pm\pi/3$ according as b is positive or negative; and the maximum value of (11) will occur for $\theta = \pm\pi/6$ according to the same conditions. Inserting these values we find for the worst conductor:

Three phase

$$1.172 + m^2 + 1.433\,m\,.\cos\phi \pm 1.172\,m\,.\sin\phi \qquad (12)$$

Six phase

$$0.347 + m^2 + 0.955\,m\,.\cos\phi \pm 0.347\,m\,.\sin\phi \qquad (13)$$

Finally, averaging (**10**) and (**11**) for variations of θ we have:

Three phase rotor loss

$$m^2 + 0.63\,[1 \pm m \,.\, \sin \phi] \qquad (\mathbf{14})$$

Six phase rotor loss

$$m^2 + 0.175\,[1 \pm m \,.\, \sin \phi] \qquad (\mathbf{15})$$

Item	Phases	Power Factor on Com.[2]	Power Factor on Slp. Rs.	ϕ (degrees)	Motor side	Amperes on Com.[2]	Amperes on Slp. Rs.	Rotor speed higher or lower	Percentage Losses Worst Cond.	Percentage Losses Rotor
Excluding magnetizing current.										
1	Three	Any			Either	1	1	Either	117	63
2	Six	"			"	1	1	"	35	17.6
Including magnetizing current, taken at 30 per cent of load current:										
3	Three	1	0.956	0	Either	1	1.045	Either	126	72
4	"	0.8 lag	0.66 lag	− 36.9	Slp. Rs.	1	1.21	Lower	183	83.7
5	"	0.8 lead	0.935 lead	+ 36.9	"	1	0.855	"	139	60.7
6	Six	1	0.956	0	Either	1	1.045	Either	43.5	26.6
7	"	0.8 lag	0.66 lag	− 36.9	Slp. Rs.	1	1.21	Lower	73.5	29.8
8	"	0.8 lead	0.66 lag	− 36.9	"	1	1.21	Higher	73.5	29.8
9	"	0.8 lead	0.935 lead	+ 36.9	"	1	0.855	Lower	60	23.4
10	"	0.8 lag	0.935 lead	+ 36.9	"	1	0.855	Higher	60	23.4

For the purpose of illustration, we give in the tabulation herewith some numerical values for the different cases discussed. We take a magnetizing current equal to 30 per cent of the current on the commutator side, or $m = 0.3$, and we give the losses as percentages, in terms of the losses due to the current at the commutator side only.

It will be found that the expressions given later, in a different form, see (**16**) to (**19**), allow a clearer appreciation of the manner in which the loss is influenced by the conditions of operation than those set down above.

The previous results may be put into a different form which will sometimes be more convenient of application. In the case of an actual machine we shall know what figure to use as an equivalent resistance r such that if I_2 is the (r. m. s.) current per commutator brush stud, $I_2^2\,r$ will be the total loss, W_2, in the armature winding due to the commutator currents alone flowing. Similarly the same value r in $I_1^2\,r$ will give us the loss W_1 due to the slip ring currents alone flowing in the armature winding, the current into each slip ring having a (r. m. s.) value equal to I_1. The magnetizing current, for which our symbol is $m\,I_2$ will similarly cause a loss, if flowing alone, denoted by W_0 and given by $(m\,I_2)^2\,r$. Further, in an actual case we shall know what value to take for r', *viz.*, an equivalent resistance such that the loss in "the worst conductor" due to the several currents taken separately is given respectively by the expressions $I_2^2\,r'$, $I_1^2\,r'$, $(I_2\,m)^2\,r'$. These losses we shall also denote by W_2', W_1', W_0' respectively.

Now the various expressions we have deduced for the mean value of the net current squared, in a conductor, or for the average value of this throughout the rotor, were based upon a commutator brush stud current such as to give unit (r. m. s.) value to the current of this frequency in the conductor. For any different brush stud current, I_2, we shall have a correspondingly altered slip ring current; also m will be changed, since the actual amperes of magnetizing current remain independent of I_2. However, by multiplying the previous expressions by $I_2^2\,r$ or by $I_2^2\,r'$ as the case may require, we shall have the correct loss expression for a brush stud current of I_2 amperes, and we can rewrite them in terms of W_1, W_2, W_0 etc., since we have:

$$W_0 = (m\,I_2)^2\,r \quad W_1 = (a^2 + b^2)\,I_2^2\,r \quad W_2 = I_2^2\,r$$

and corresponding equations in W' and r'; and by means of these we can replace m, a, b, etc. Thus, from the definition of a, b, we have:

$$(1 - a)^2 + b^2 = m^2$$

and therefore:

$$2\,a\,I_2^2\,r = W_1 + W_2 - W_0$$

Expression (**14**) which, upon multiplication by $I_2^2\,r$ is equivalent to $[m^2 + 0.63\,a]\,I_2^2\,r$, becomes when re-written:

$$0.315\,(W_1 + W_2) + 0.685\,W_0 \qquad (\mathbf{16})$$

and represents the three-phase rotor loss; while the six-phase rotor loss is similarly found from (**15**) to be:

$$0.088\,(W_1 + W_2) + 0.912\,W_0 \qquad (\mathbf{17})$$

In precisely the same way the loss in any one conductor at position θ can be written down in the new terms, from expression (**10**) and (**11**), *viz.*

For three-phase;

$$W_0' + 1.655 \cot\phi \sin\theta\,W_2' + [1 - 0.827 \cos\theta - 0.827 \cot\phi \sin\theta]\,[W_1' + W_2' - W_0'] \qquad (\mathbf{18})$$

For six-phase;

$$W_0' + 1.91 \cot\phi \sin\theta\,W_2' + [1 - 0.955 \cos\theta - 0.955 \cot\phi \sin\theta]\,[W_1' + W_2' - W_0'] \qquad (\mathbf{19})$$

In expressions (**18**) and (**19**), ϕ is introduced as well as the W' *s*. The conditions of operation are really completely defined when we are given the values of the three W' *s*, a statement as to which side is the motor side, and the two frequencies (including their relative signs); hence the presence of ϕ might be avoided. In fact an inspection of the vector diagram for the three current components (f_1 load, f_2 and f_1 magnetizing) will reveal that

$$\sin \phi = \pm \frac{W_2 + W_0 - W_1}{2\sqrt{W_2 W_0}}$$

the upper or lower sign being taken according as the slip ring side is acting as the motor or generator side. Hence ϕ might be eliminated by means of this equation; or alternatively, in an actual case it may be determined from this equation, if not independently known, and the value used in the expressions given.

The reference numbers of the expressions derived in this chapter for the conductor and rotor losses under various conditions and allowing for magnetizing current are collected below for convenience of reference;

	Three-Phase	Six-Phase
For loss in whole rotor.....	14	15
Ditto, in terms of W_0, W_1, W_2	16	17
For conductor loss.........	10 (12)	11 (13)
Ditto, in terms of W_0', etc.	18	19

CORRESPONDENCE

POLYPHASE COMMUTATOR MACHINES

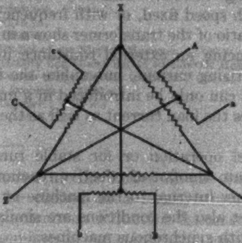
To the Editor:

An article under this heading appears in the January issue of the JOURNAL, attributed to myself. In spite of the title the Article itself deals with only one type of frequency changer, and even for that machine only discusses some of the I^2R losses, but the broad titles which appears above the article has no doubt arisen by reason of the inclusion, through some inadvertence, of the matter contained in a hastily compiled memorandum dealing with another subject, and not intended for publication; this composes the first five paragraphs and the first (unnumbered) figure of the article in question.

The error would have been avoided had proofs been submitted to me, but in the circumstances perhaps you will allow me to make some necessary corections now, in the part referred to.

On page 50 of the JOURNAL in the fourth paragraph of the article, reference is made to the characteristics which may be expected from a machine comprising an induction motor stator and a rotor having a commutator, both stator and rotor having closed windings with the same number of conductors. The rotor is supposed to be running at twice synchronous speed in the same direction as the air-gap field, and the three phase brushes to be in line with the three phase tapping points of the stator winding, or at 180 deg. to the same, according as the coil progression of the rotor winding is the reverse of, or the same as that of the stator winding. It is suggested that as the same air-gap field would be produced by a lagging magnetizing current in the stator winding as by a leading current in the rotor winding, the requisite magnetizing current might be induced to circulate between stator and rotor connected in parallel to the bus bars without the necessity of any magnetizing current being introduced from outside; also that the small IR voltage required to cause this circulation might be produced by a slight shift of the brushes, while the small IX voltage component at right angles to this, corresponding to the stator and rotor leakage fluxes associated with the magnetizing current only, might be introduced by an a-c. exciter, interposed between the line and the machine.

The statement needs a little modification in as much as the shift of brushes which provides the requisite IR voltage for the circulation of magnetizing current produces at the same time a compounding effect, and would therefore have to be determined by the amount of such compounding desired; the balance one way or the other would have to be obtained otherwise, for instance by the transformer connection referred to later. Further, the IX voltage required would automatically appear by a slight slip arising, that is, by the air-gap field taking up a speed of rotation slightly different from half the rotor speed; therefore no a-c. exciter need be postulated. For operation with shunt characteristics the brushes would be left in the normal position, and a small quadrature voltage would be injected between the stator and rotor to overcome the IR drops corresponding to the circulation of magnetizing current only; this quadrature voltage might be introduced by the delta-connected transformer arrangement shown in the appended figure, the lines $A\ B\ C$ going to the stator and $a\ b\ c$ to the rotor, while $X\ Y\ Z$ pass to the busbars. The transformer might advantageously have a moderate magnetic leakage.



The last two statements of the fourth paragraph substantially stand, to the effect that in a machine such as here described the field rotates in the same direction as the rotor at approximately half the speed of the rotor so that a rotor conductor cuts the field in a direction opposite to that in which the stator conductor, immediately confronting it, cuts the same field, the two speeds of cutting being nearly the same; and that therefore, whether the machine be running as a generator or motor, almost complete compensation takes place of the stator ampere conductors by the rotor ampere conductors immediately confronting them and the machine becomes closely self-regulating.

It will be seen further that although the machine operates with some slip, it behaves more like a synchronous generator or motor than an induction machine inasmuch as there is one combination of frequency speed and voltage which forms a consistent set of conditions, and the only natural flexibility in the relation between the frequency and speed is that introduced by saturation which causes a variation in the ratio between the IR and IX components of voltage requisite for circulating the magnetizing current. The slip will not change sign between generator and motor conditions of operation, in fact it arises only to provide voltage for circulating magnetizing current and not for load current. A slight variation in frequency with speed fixed can be artificially secured however by introducing an external inductance in the path of the circulating magnetizing current; such inductances may, if desired, be so arranged as to be substantially non-inductive to the passage of load current, although inductive to the circulation of magnetizing current. Similarly the voltage can be varied with speed fixed, or with frequency fixed, by varying the ratio of the transformer shown in the figure, or by introducing an external resistance in the path of the magnetizing current, but unlike the inductance the resistance can only be introduced in a manner such that it opposes the load current as well as the magnetizing current.

For parallel operation or for stable running as a motor, a certain amount of effective reactance will be necessary either internal to the machine or accessory. In this respect also the conditions are similar to those which arise with synchronous machines.

These features of operation are detailed here, not with the intention of claiming practical utility for the arrangement, but merely to correct the somewhat erroneous view of the matter which has already been printed in the article in question.

While upon this subject it may be of interest to consider the conditions arising at twice synchronous speed in the frequency changer dealt with in the main part of the article. If we assume the rotor of say a three-phase frequency changer of this type to be independently driven at twice synchronous speed in such direction that the frequency is the same on the commutator as on the slip rings, we have two three-phase systems of equal frequency and voltage associated with the machine. The phase rotation on the commutator is the reverse of that on the slip rings considering corresponding brushes but nevertheless the two three-phase systems can be paired and brought into phase with one another and then there would seem to be no objection to paralleling them on to common bus bars. The machine will then be running on the bus bars without distress with commutator brushes solidly connected to slip ring brushes, a somewhat paradoxical condition. Here again the arrangement is of theoretical interest only and has no practical utility, it acts neither as generator, motor nor converter; it might serve as a filter to short-circuit all effects other than those of fundamental frequency.

Glancing over the main part of the article I note that ambiguous signs are invariably printed with the plus as the upper and the minus as the lower sign, whereas they should be reversed in the case of the expressions numbered 8, 12, 13, 14, 15 and in the definition of a on page 55. Without these corrections the tabulation would appear to be wrong and the matter troublesome to follow. A. B. FIELD.

The Electric Hammer.

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Review of the Subject.*—The power hammer has been in use for a long time and there are now on the market many types of power-operated hammers which may be roughly classed according to the nature of the power as follows:*

Pneumatic, steam, motor and pulley; cam or crank, and electro-pneumatic drives. The pneumatic drive includes all riveting hammers; the steam drive includes practically all forge hammers, some drop hammers, pile drivers and steam drills; the motor and pulley drive class, includes the greater part of drop hammers; the electro-pnuematic drive includes only small forge hammers. The pneumatic hammer, due to its lightness, holds the field of hand-operated riveting hammers and it is hardly possible that any other means will ever surpass air for driving hand-operated riveting hammers; the steam hammer holds its own in very large forging and drop hammers and it is doubtful whether any other kind of hammer can remove it from that place. The field for very large forging or drop hammers is however rather limited; they are used only in very large plants in which all sorts of power prevail.

There is an immense field, however, for medium and small forging and drop hammers which are used to produce all the small automobile and other similar parts as well as name plates, jewelry apparel, etc. It is this field which the electric hammer is supposed to cover. The present methods of driving these hammers are cumbersome, complicated, costly and very unsafe for the workman.

The electric hammer has been studied and developed by the writer to a point where it seems to show superiority to the present used hammers, in simplicity, safety, running expenses, cost of installation, cost of upkeep and in many cases in the original cost.

The development shown herein is of the induction motor type. Instead of the usual arrangement of concentric armature and field, the slots are punched on long strips of iron in a straight line which makes the field and armature parallel.. The armature and field still face each other but every part of the aramture is not always active under the influence of the field as is the case in the ordinary motor. In other words in a straight-line motor the armature or runner is continuously entering the field of action at one end and leaving it at the opposite end. This constitutes the main difference between the straight-line and the rotary motor. The rotating fields of an induction motor are here replaced by magnetic fields moving in a straight line. The principal elements of this straight-line induction motor hammer are shown in Fig. 3. The actual hammer as finally constructed is shown in Fig. 5 (back view) and Fig. 6 (front view.)

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DEFINITIONS

An electric hammer as described in this paper constitutes a hammer in which the reciprocating part is moved solely by the direct action of the electromagnetic forces without interposition of any other mechanism, such as belts, gears, compressed air, etc.

The electrical portion of the reciprocating part, which is analogous to the rotor of a motor, will be called the runner while the die holder which is attached to the runner is called the ram.

Electric hammers may be divided into four classes: Direct-current, semisynchronous induction, nonsynchronous induction and purely synchronous. A direct-current hammer consists of two symmetrical straight armatures mounted facing each other between which moves the field carrying with it the brushes; it may also be made with two stationary fields and one moving aramature. A semisynchronous induction hammer is made by setting two polyphase straight-line stators facing each other with a squirrel-cage runner moving between them; the reversal of the current is made by a switch rigidly connected to the generator shaft so that the phases are reversed at zero potential and at predetermined intervals. A two-phase hammer fed with two phases of different frequency in which the reversal comes at the nodes of the two frequencies may also be classed as a semisynchronous hammer.

A nonsynchronous induction hammer is made exactly as a semisynchronous induction one with the exception that the reversing of the phases at each end of the stroke is done by the runner itself. A purely synchronous hammer may be defined as a hammer which gives one stroke per cycle. This type of hammer may be made of the simple plunger type or of the excited plunger type.

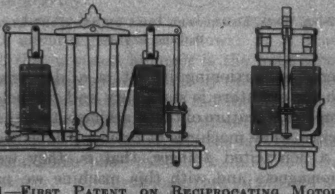

Fig. 1—First Patent on Reciprocating Motor
Issued in 1852.

HISTORICAL

The writer invented the electric hammer early in 1915, when still in school. After coming out of school, the war was in full swing and it was thought inadvisable to start developments of any kind. The studies were

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Presented at the Spring Convention of the A. I. E. E., Chicago, Ill., April 19-21, 1922.

made independently but the following historical treatment will show that it was not an invention but a reinvention.

The subject of the reciprocating motor in general is practically as old as that of rotary motors; this fact is shown by the records in the Patent Office from which it is seen that the earliest attempts to make electric motors were mainly along the lines of imitating the reciprocating steam engine and the first patent for a reciprocating motor to be applied to a pump was issued in 1852; a picture of this device is reproduced in Fig. 1. In 1870, there were some attempts made to operate sewing machines with reciprocating electric motors. In 1880 appear two patents on a solenoid rock drill. In 1885, the Van Depoele patent appears. This patent is reproduced in Fig. 2 from which it may be seen that engineering was, at that time, being applied to this line of inventions, for it is quite a well developed machine which may easily be made practical by properly proportioning it. It is a d-c. machine in which the armature is stationary and the field moves. An important feature of this machine is that the plunger is excited while machines of previous dates were made with a nonexcited plunger, that is, they were mere electromagnets and with this machine we pass from electromagnets to straight-line motors. The idea of plunger reciprocating motors and straight-line d-c. motors prevails until the present time and it would be useless to recount here the innumberable patents that have been issued on the subject. It may be said, however, that the idea remains unchanged and the only thing that changes is the inventor.

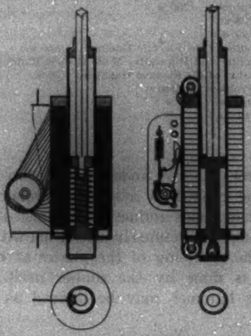

Fig. 2—A Well Developed Idea on Straight-Line Motors Patented in 1885.

In August, 1901, a patent was issued to R. D. Mershon on a straight-line nonsynchronous polyphase induction motor for a rock drill. He mentions in his specifications that prior to that time polyphase rectilinear motors have been proposed in which the reversing of the fields was done by a switch connected to the generator; that system he condemns because the vibratory period of the motor would have to be of certain value in order to be in synchronism with the generator, and consequently it would not start from rest unless those conditions were fulfilled. His system has a reversing switch operated by the moving part of the motor and consequently makes the latter completely independent of the generator. As far as the writer can find, this is the first record of a practical polyphase rectilinear motor.

In 1905, a patent was issued to P. Centener. This machine is based on an entirely new principle. In this machine, each stator is fed with two separate sources of alternating current of different frequencies and in this way the motion of the field is reversed at the beats occurring in the two frequencies so that the moving part would reverse its motion without the necessity of reversing the currents by means of contactors or switches. While this machine is built on different principles from those criticised by Mershon, its faults are the same, namely: It has a constant period and it requires special generators to operate it.

In 1909, a patent was issued to T. F. Bailey in which the same invention as is shown in Mershon's patent was described with the exception that the application is made directly to a forge hammer instead of to rock drills.

The success of these inventions in rectilinear motors is apparent from the fact that none of them are at the present time on the market. Of the semisynchronous hammers, the only successful machine that the writer knows of is that made by Professor Leo Schüler of Berlin, Germany, described in U. S. Patent No. 1115251. He actually made a small chipping plunger hammer that would work successfully. From his account in the *Elektrotechnische Zeitschrift*, it is hard to understand why the machine has not been put on the market unless it is for the reason that it requires special generators for the supply of power. It is not known to the writer whether or not there have been built any polyphase rectilinear motors operating on the principle brought out by Mershon, that is, in which the reversing is done by the motor itself. Mr. Charles Fair, who was employed by the G. E. Co. at the time this work was started, said that he had seen a model of the d-c. plunger-type hammers which he described as not being "lively" enough for forging purposes. The machine, as he described it, was made up of a series of solenoids in which moved a plunger. The plunger was first attracted by one solenoid, the current was then switched to the next one and the plunger moved with the current. Irrespective of whether this machine was "lively" or not it is easy to see what difficulties would be encountered in shifting the current from one solenoid to another at the time of maximum inductance. In other words, it may be said that this machine was a very badly designed direct-current motor.

The reasons why the electric hammer was not developed appear to be the following: In the early days of electrical development the demand for hammers was rather small; rotary motors could be used for many more applications than the special uses for which the straight-line motors were proposed; hence it became much more remunerative to develop rotary motors than to develop straight-line ones. Once a rotary motor was available in its perfect form it became much easier simply to take a standard motor and apply it to the particular use for which it was needed than it would have been to develop a new special motor.

It may be said further that in the early stage of electrical development, the total demand for motors was very small and of this total demand the percentage which required an ordinary standard motor was far greater than that which required a special straight-line motor, so that it was altogether out of question for any manufacturer to undertake the development of as many special motors as there were special cases to be taken care of. At the present stage of electrical industries, the conditions are precisely reversed in that there are now many special cases which require a much larger number of motors than was required for the total electrical industry in the earlier days of the art and certainly anybody who is acquainted with the industry will agree that many manufacturing enterprises are now existing, and in fact prospering in the manufacture of only one or two special appliances. It is for this reason that it is felt justifiable to state that the application of standard rotary motors to special cases has gone beyond its limits.

The above is, it is hoped, the answer to the many questions that are continually being asked as to why it is that nobody else has ever tried to develop an electric hammer before this if it is as simple as it looks. It is also an explanation of the arguments which led to the undertaking of this development.

As a matter of fact, it is felt that the development of a new special machine will always be justified as long as the demand for it is large enough to build up a reasonable amount of business and its qualities are such as to guarantee its preference to existing systems.

Preliminary Studies of the Electric Hammer

When the study of the electric hammer was undertaken, the subject was so new from an engineering view point that a preliminary study was required in order to decide which system of those mentioned would be the best to use, also to determine fully the advantages of an electric hammer over those hammers which it was to replace.

In studying the problem in general, it is found that an electric hammer is essentially an apparatus which is continually starting and stopping; electrically, therefore the apparatus best fitted for this purpose would be an apparatus which gives the best efficiency during the starting period. A d-c. series motor is evidently the best apparatus to use for such purposes. On the other hand, a power hammer must be so constructed as to withstand shocks without limit either in number or in size and it was doubtful whether any commutating apparatus would be capable of withstanding such rough usage as that even though the armature and commutator may be made the stationary part and the field allowed to move. The problem therefore, resolves itself into three branches; one consists of the study of the properties of the electric hammer to predetermine its advantages over the hammers which it shall replace; the second consists of a study of its mechanical stability and durability under repeated and violent shocks; and the third is a study of the electrical properties of the machine as affecting an apparatus which is continually starting and stopping.

The problem of determining the advantages of an electric hammer over a board hammer had to be resolved from fundamental considerations rather than from existing facts because there were no facts available. The main points of merit of the electric hammer were the following:

In cases where it replaces board hammers, it consumes no power while not working, there are no moving parts while it is not operating, it is neater in appearance, it occupies a minimum of floor as well as overhead space. There are no parts to wear out, outside of the runner, and the contactors (which in the final design will be made so easy to replace that it is expected will give no more difficulties than an ordinary board hammer). It is very easy to move it from place to place. The most prominent feature of an electric "board" hammer is its great variety of the size of blow that it can give, ranging from zero to four or five times as large a blow as it could give by merely falling under the action of gravity.

When the electric hammer is made to replace a steam hammer its advantages are as follows: It is a well-known fact that a steam hammer is the most accomplished waster of energy ever made by the human hand, considering all condensation on the lines, which are sometimes of great length, all the steam used to keep it warm while not in operation, and the fact that sometimes a special boiler plant must be installed to operate a steam hammer. All these losses are eliminated with an electric hammer; there can be an electric hammer wherever there is an alternating-current supply, it can be moved from place to place without much difficulty; since it can be tied to any supply system, the small manufacturer can have it, in other words anybody may have a power hammer. These qualities are what could be foreseen before any test was made or even before any hammer was ever designed.

Mechanical Stability and Durability of an Electric Hammer

Here again it was a case of predetermining these qualities from facts which were more or less self evident, because no actual apparatus had ever been built. The facts which were very apparent were the following: Compared with the board drop hammer it may be said that the runner of the electric hammer replaces the board of the board hammer, hence the electric hammer has nothing to get out of order except its "board;" against the elimination of all those parts must be set the introduction of at least two pairs of contactors (in case the third one is introduced, electrically it is possible for only two to work since two of the three are in series and either of these two must open the circuit). Also the question came up as to whether the runner of the electric hammer would withstand the severe shocks to which it must be subjected. This question may be considered from two standpoints, first if it is made of laminated steel with copper bars for the squirrel cage, the construction is apparently weak but on the other hand, it has that elasticity which absorbs the shocks much better than any solid construction can absorb them and prevents breakages.

A laminated runner is a rather costly construction but it is believed that it would last longer than a solid one and certainly much longer than boards last in ordinary board hammers. The other alternative was to make the runner of solid steel which would, by reason of its simplicity, cost so little that the replacement of it would not be at all expensive nor would it be any more difficult to renew a solid steel runner in an electric hammer than it would be to renew a board in a board hammer.

Compared with the steam hammer, it may be said that the troubles given by the steam hammer by the breaking of the piston rods on account of the crystalization which occurs where the rod connects to the ram of the hammer might be eliminated to a great extent by a laminated construction which is perfectly possible with the electric hammer, but I do not think it would be feasible in case of a piston rod which has to fit steam tight in the cylinder head (it must be remembered that outside of the ways which guide the runner in a vertical direction, it may be said that the latter hangs almost free in the air). In short, it was thought that the worst expectation that we could have was that we might have as much breakage from an electric hammer as from a steam hammer and certainly all the rest of the conveniences obtained by an electric hammer were thought to be enough to justify the change.

Field of Application of the Electric Hammer

If we consider the replacement of all steam hammers, board hammers, pile drivers and all like apparatus, the field is certainly sufficient to justify the development and marketing of such an apparatus.

The Electrical Problem

From the electrical standpoint and from the long study previously made on d-c. motors (especially the series motors), it appeared always preferable, ever since the problem was undertaken, to build a direct-current series machine; therefore proceeding on this belief, a direct-current reciprocating motor was designed and its main characteristics calculated. The runner of this machine was to be the field and was to be made of solid steel in which there were slots for the distributed field windings. The field coils were to be retained in the slots by nonmagnetic materials such as brass or bronze, and the brushes were to be carried by this moving part. The armature was to consist of two straight-line armatures, one on each side of the field, each having its own commutator so that the two might be connected either in series or in parallel with each other. (The double armature was of course necessary to balance the electromagnetic forces as well as to utilize the field metal to its fullest extent). The electromagnetic properties of this machine were found to be very excellent; the starting current was rather small and the torque per watt very large; it can be designed for very low speeds. In general, it showed the superiority of d-c. to a-c. in case of motors which have to start and stop continually under heavy load. The electromagnetic force per pound of the active metal of the runner was very high as compared to that of the induction motor. In power hammers, and especially in the so called drop hammers where the ram must be heavy enough to hold the die, it is very important that the electromagnetic force per pound of active metal be as large as possible so that most of the metal con-

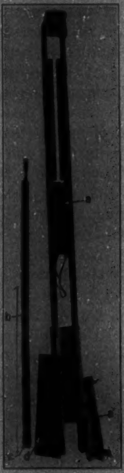

Fig. 3—First Experimental Electric Hammer

a—one of the stators mounted on the wooden frame, *a'*—the other stator dismounted, *b*—the armature or runner (a piece of brass $^1/_8$ in. by $2\frac{1}{4}$ in.) removed, *c*—the ram, *d*—a guarding plate making a part of the framework.

stituting the total weight of the moving part may be placed on the ram. In electric hammers, this point is of even greater importance since the power may be applied downward and the total weight of the moving part must be decreased very much to obtain the proper rating.

In spite of the preference which the writer had for the direct-current machine, it was repeatedly pointed out that it would not withstand the shocks of a hammer and it was finally recommended that the polyphase induction type be looked into before definite plans were made for building any hammers at all.

Under these suggestions, a very small model of polyphase straight-line motor, in which the moving part was made of a piece of brass 1/8 in. thick by 2½ in. wide, was built and tested. This hammer was equipped with a heavy piece of cast iron on the bottom end and also with an automatic reversing switch so that when power was applied it would reciprocate up and down like an ordinary hammer. An illustration of this crude model is shown in Fig. 3. It should be understood that this model was not made to obtain engineering data nor was it designed to give any definite result. The object of building it was merely to show the several people interested that such a hammer would work. The model proved very satisfactorily how much simpler a polyphase hammer is than a direct-current one.

After several lengthy discussions with engineers who were well acquainted with the power hammer problems, it was concluded that it would be best to start the development by building a polyphase induction hammer.

In accordance with this decision, a hammer was designed to operate a 200-pound ram, in other words, a hammer which would be equivalent to a so-called 200-pound board hammer, this comparison of course being made in a case when the electric hammer lifts a 200-pound ram, and lets it fall by gravity; in case power is added on the downward stroke its capacity would be greatly increased as will be shown in the results of the tests. For the purpose of obtaining engineering data, the runner was made of laminated steel.

It was apparent from the character of the working cycle of this machine that the runner should be made of high resistance in order to obtain high starting torques, high power factors and at the same time draw a small starting current from the circuit. This was done by using brass bars in the squirrel cage; in addition to that, both for convenience in building it and to diminish leakage reactance, the secondary slots were made open and the bars made even with the surface of the steel laminations. Making the bars even with the surface also eliminates all that portion of the primary leakage flux which passes from one tooth to the other above the secondary conductor.

About the worst thing to contend with, at least during the discussions of this apparatus, was the so-called end effect that occurs when a conductor of the rotor passes out of the stator field into the air. This difficulty, as pointed out by Dr. Steinmetz, had been one of the main difficulties which led to the abandonment of the induction railroads. To the end-effect problem, as related to this hammer, there was at least one solution and that was to be found from the fact that the efficiencies of the present hammers are so small that it was thought almost impossible to make a straight-line motor bad enough to compare with the present hammers, in other words, one solution of the problem was not to solve it at all.

Accordingly, the hammer was built with the following dimensions: Length of stator, 39 inches, length of runner 5 feet, and width of the cores, 2½ inches, or in other words, the motor was very nearly "square." It was assembled in a box made of boards 2½ inches thick, which was provided with brackets for mounting it on the uprights of an ordinary 200-lb. board hammer. The construction was made so crude because it was still doubtful in the minds of a good many of those concerned in the development as to whether it would be successful or not. The standstill characteristics were then obtained and the most important curves are shown in Fig. 4.

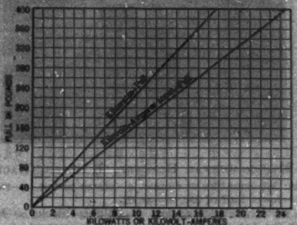

FIG. 4

Curves showing the relations between the total kilowatts input and the total pull exerted on the runner; also the relation between the total kilovolt-amperes input and the total pull exerted on the runner.

It was finally mounted on the uprights and since the 5-ft. runner was too short to reach to the anvil, it was found necessary to make a wooden block high enough so that it could be operated with the given runner. The switch mechanism consisted merely of a reversing knife switch automatically operated by the moving part and no connection was made between the switch mechanism and the treadle, so that to start the hammer it was necessary to close the main switch. Once it was closed the hammer kept on going up and down at the rate of about three strokes per second.

This model, as crude as it was, was sufficient to show that the electric hammer was a success. In addition to that, we obtained starting currents, and power factor, and cleared in this way all those questions which were up to that date a stumbling block for the development; it was shown, in other words, that operating an electric hammer did not wreck the supply system, as was thought by many. No photographs were taken of this model when it was mounted, but outside of the wooden anvil, it was exactly the same as that shown in Fig. 6. Having cleared all these difficulties, it was decided to build a real model capable of performing the same functions as an ordinary 200-lb. board hammer.

In the new model, the same stators were used and the work of the new design consisted merely of designing a pair of uprights together with the proper automatic switching mechanism necessary to have the electric hammer operate analogously to the board hammer.

Fig. 5—Experimental Electric Hammer (Back View)

Main parts: *p*—armature or runner, *q*—stator casing, *x*—ram, *u*—upper half of die, *v*—lower half of die, *w*—anvil.

Auxiliary parts: *a*—holding dog, *b*—holding block, *s*—spring which actuates both the dog *a* and the lever *c*, *e*—a lever crank, *f*—cut-out contactor operated by dog *a* through lever *c*, *r*—switch for controlling power on downward stroke.

At this point Mr. D. C. Garroway, an engineering draftsman, began to assist me in the development of the present model.

The cycle of operation of an ordinary drop hammer is as follows: Ordinarily, a hammer hangs up in place and when the treadle is pressed, it falls down and automatically returns up to its original position and keeps on going up and down as long as the foot is kept on the treadle. As soon as the latter is released no matter where the hammer is it continues its operation until it gets up to the upper position and hangs itself there ready for the next operation. It was necessary, therefore, that an electric hammer be capable of performing the same cycle. To do this, it is essentially necessary to have a cut-out contactor and a pair of reversing contactors. The cut-out contactor must be operated automatically by the moving part so that when the hammer hangs itself on the upper position the circuit is open. The reversing contactors are for the purpose of reversing two of the three phases at each end of the stroke. The opening and closing of contactors must be done at a constant speed irrespective of the speed of the moving part of the hammer.

In addition to these three contactors, it was decided to add a fourth one for the purpose of cutting off the current on the upward stroke before it had actually reached the end of the stroke in order to save power and also avoid the necessity of reversing at full speed.

Fig. 5 shows a back view of the hammer with the ram in its upper position. At *b* is shown a block fastened to the ram which engages with the dog *a* fastened to the uprights. The dog has an elliptical hole at its fulcrum so that when the ram comes down on it, it moves downward a half inch before it gets to the bearing. On the same dog is fastened the lever *d*, which is connected to the treadle and also a vertical flat piece of steel *c*, free to move up and down a half inch with the dog *a*. This piece of steel operates a lever *e* which in turn operates the cut-out contactor *f*. Therefore, when the hammer comes down on dog *a*, it hangs itself and also cuts out the main circuit.

The spring *s* has two functions, one is to keep the dog *a* in its upper position and in that way keep the contactor *s* closed, and the second function is to keep the dog *a* always turned to the right under the block *b*. The vertical motion of *a* and therefore that of *c* is always quick and consequently no additional mechanism was needed to make the opening of the contactor fast enough to eliminate burning.

Fig. 6—Experimental Electric Hammer (Front View)

Main parts: *Q*—motor casing in which stators are mounted, *P*—armature or runner, *X*—ram, *U*—upper half of die, *V*—lower half of die, *W*—anvil.

Auxiliary parts: *R R'*—follower rods, *f f'*—followers, *TT'*—cams, *C'*—cut-off contactor, *C*—one of reversing contactors, *A A'*—switching arms operated by *R R'*, *S S'*—switching springs, *K K'*—contactor cranks. Arm *A* moves spring *S* to one or the other side of *K* and the spring does the switching.

Fig. 6 shows a front view of the hammer also with the ram in its upper position. The two rods *R* and *R'* carry the cams and levers to operate respectively reversing contactors C and the "cut-off" contactors C'. These rods are made long enough to be able to get the stroke of any desired length from zero to the length of the uprights. The cams that are fastened on these rods are operated by two studs T and T' fastened to the ram. The arms A and A' also connected to these rods operate the reversing contactors and the "cut-off" contactors respectively. In order to assure a constant opening and closing speed of the contactors, the opening is done through springs S and S'. All that arms A and A' have to do is to move one end of the spring S and S' on one side or on the other of the center of the contactor cranks K and K' and the opening and closing after that is performed by the springs independently of the cams or the moving part of the hammer and hence it is done always at practically the same speed, which can be adjusted by adjusting the tension of the spring and its eccentricity.

FIG. 7—OSCILLOGRAM OF ELECTRIC HAMMER OPERATING WITH ELECTRIC POWER ON UPWARD PART OF STROKE ONLY, GRAVITY PRODUCING THE HAMMER BLOW.

The upper vibrator gives a smooth wave of a 40-cycle voltage which is used for measuring time. The middle vibrator shows the deflection of a direct current obtained from a dry cell which has its circuit momentarily closed at every inch of movement of the armature or runner. The time taken for the runner to move through one inch is measured by the distance between "making" points which are marked 1, 2, 3, etc. on the record of the approximate zero of the middle vibrator.

The lower vibrator shows the current of one of the three phases.

The distance between the vertical lines A and B indicates the time of one complete stroke (or cycle of operation).

Starting from the point A when the alternating current ceases the runner continues on its upward stroke until it uses up its momentum at some point about the position marked C. It then begins to fall slowly by gravity, as shown by the distance between the vertical lines of the middle vibrator, and gradually accelerates until the hammer strikes. Shortly after, the current to lift the runner comes on again for eight and a half cycles to point B where the cycle of operation starts to repeat.

Since this hammer is provided with reversing mechanisms, it is evidently possible to apply power on the upward as well as on the downward stroke and here is where the electric hammer differs from the board hammer. In order to cut off the power in downward stroke, it is necessary to have also an ordinary knife switch in series with the circuit for the downward stroke. This switch may be seen at r in Fig. 5. By changing the position of the cam F', it is possible to regulate the length of "admission" and by changing the position of F, it is possible to regulate the point of reversal. The length of the stroke can be changed only by changing the position of a in Fig. 5 and that can be done only by moving the steel block m upon which a is fixed. Holes are provided on the upright and also on the steel piece c for changing the length of strokes.

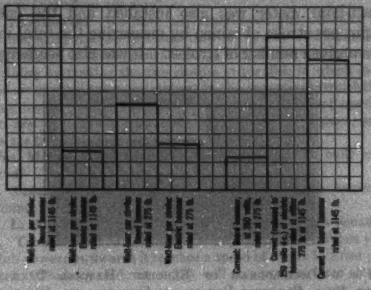

FIG. 8—CHART GIVING COMPARISON BETWEEN ELECTRIC HAMMER AND BOARD HAMMER WHICH IT IS TO REPLACE

Comparison of efficiency is made in watt-hour per stroke. Current efficiency is given in amperes. The hammers are compared both at a rating of 275 lb. and at a rating of 1145 lb.

It is evident that by inserting resistances in series with the downward circuit, we may apply any amount of power ranging from zero to full value on the down-

TABLE I.

Working Characteristics of Hammer Already Existing

Kind of Hammer	Hammer Number	Rating in Lb.	Total Time Hours	Total Strokes	Useful Strokes	Average Strokes per Hr.	Average Useful per Hr.	Max. Strokes per Hr.	Max. Useful Strokes per Hr.
Board	1	400	6	5900	5900	984	984	2060	2060
Board	2	400	4.5	7645	7645	1700	1700	2475	2475
Board	4	600	12.0	9740	9740	810	810	1400	1400
Board	5	800	6	1610	1610	170	170	315	315
Board	6	800	12.25	3646	3646	297	297	403	403
Air	8	700	2	3226	3226	1613	1613	2322	2322
Board	11	600	6	4591	4591	772	772	985	985
Board	17	1200	6	3857	3857	642	642	702	702
Board	20	1200	6.5	2327	2327	358	358	468	468
Board	22	1600	3	1173	1173	391	391	500	500
Board	24	1600	6	1542	1542	257	257	483	483
Steam	32	3500	6.5	21800	2971	3350	429	3600	795
Steam	34	2500	3.0	8120	1128	2707	376	3480	898
Steam	37	1000	6.0	9075	2107	1512	351	3000	881

ward part of the stroke. Also by making the switch *r* a reversing switch, we may apply upward power on the downward stroke also from zero to full value. This gives a range of blows from zero to a blow given when full power is applied downwards.

TESTS OF THE HAMMER

In order to test the hammer it was necessary to obtain the speed at the time of impact, the upward and downward accelerations, current at starting and on running, energy input per stroke etc. The oscillograph method was the only method available to do all this. The hammer was therefore equipped with a sliding contact mounted on the ram and made to slide against a long piece of fiber in which there was a strip of copper imbedded at intervals of one inch. In Fig. 5, *h* is the fiber block and *k* is the sliding contact. A watt-hour meter was also installed and the energy input per stroke obtained by measuring the total input for a given number of strokes. It was also necessary to study other hammers in order to make a clear comparison between the electric hammer and the ordinary types.

FIG. 9—OSCILLOGRAM OF ELECTRIC HAMMER OPERATING WITH FULL ELECTRIC POWER ON UPWARD AND DOWNWARD PARTS OF STROKE

The upper vibrator gives a smooth wave of a 40-cycle voltage which is used for measuring time. The middle vibrator shows the deflection of a direct current obtained from a dry cell which has its circuit momentarily closed at every inch of movement of the armature or runner. The time taken by the runner to move through one inch is measured by the distance between "making" points which are marked 1, 2, 3, etc. on the record of the approximate zero of the middle vibrator.

The lower vibrator shows the current of one of the three phases.

The distance between the vertical lines *A′* and *B′* indicates the time of one complete stroke (or cycle of operation).

Starting at the point *A′* when alternating current is switched on for the downward stroke the runner starts to fall under the joint action of gravity and electricity accelerating quite rapidly, as shown by the successively decreasing distance between the vertical lines of the middle vibrator, until after six cycles the hammer strikes at about the position marked *C′*. Shortly after the current to lift the runner is again switched on for a period of eight cycles after which the hammer keeps on moving upward until it practically uses up its momentum and the reversing mechanism operates to switch on the downward power at point *B′* when the cycle of operation starts to repeat.

In the oscillogram of Fig. 7 is shown (between the two vertical lines) the current per phase, a 40-cycle timing wave, and in the middle line is shown the timer. In this oscillogram it is found that the total time required for one complete stroke when the hammer falls down by gravity is $\frac{26}{40} = 0.65$. sec. The time during which power is being admitted is $\frac{8.5}{40} = 0.21$ sec. The average current per phase is 109 amperes.

The energy input per stroke, when falling down by gravity, as found by the watt-hour meter is 1.6 watt-hours. The total height to which the ram and runner were lifted was 1.21 ft. giving therefore a total amount of work, done on the hammer by the motor, of $1.21 \times 275 = 333$ foot-pounds. 1.6 watt-hour $= \frac{1.6 \times 3600}{9.8} \times 7.2$ ft-lb. = 4240 ft-lb. giving an efficiency $= \frac{330}{4240} = 7.8$ per cent. In calculating this efficiency no account is taken of the friction as it was not measured at the time the tests were made. It is very probable that if the friction were considered, an efficiency of about 10 per cent would result. Under the same conditions, the board hammer gives an efficiency of $7.8 \; \frac{1.6}{3.09} = 4.05$ per cent.

In Table I are given data which were collected in the drop forge shop of the General Electric Company at Schenectady. From this table we may obtain an idea of what we may expect to be the efficiency of a steam hammer. For instance, hammer No. 32 gave 21,800 strokes in 6.5 hours and only 2971 or approximately 13.7 per cent of the total number of strokes were of use. With an electric hammer this percentage may be raised to 100 per cent and the total efficiency again becomes equal to that of the machine itself as if it were working continuously.

The chart of Fig. 8 gives an idea of the magnitudes of the different quantities involved in the comparison of the two hammers. The weights of the moving part of each of the two hammers are very nearly equal and therefore the comparisons may be made directly. In this chart one assumption is made, that if the board hammer were rated at 1145 lb. it would take four times as much current to lift it as it does at 275 lb. From the oscillograph of Fig. 9 we find that when the electric hammer works with power up and down the total time in which power is being admitted equals 14.5 waves and therefore the power per stroke equals $\frac{14.5}{8.5} \times 1.6 = 2.72$ watt-hours.

The comparison between the amounts of energy taken per stroke must necessarily be very rough because the energy per stroke taken by the board hammer is a variable quantity depending upon the amount of useful work it does in a given time that it is running, since it consumes energy while running idle, while the energy per stroke consumed by the electric hammer is constant. The efficiency of the electric hammer therefore is also a constant quantity while that of the board hammer is variable and may reach zero in case the hammer runs idle for a long period of time. It may be pointed out here that since the static condensers are now available at a reasonable price, the total kilovolt amperes drawn from the line may be much reduced by the use of such condensers. Outside of energy consideration, the following qualities have been found very favorable for the electric hammer.

Since there are no moving parts when it is not in operation, it is very much safer than a board hammer. Lately it has been equipped with a reversing knife switch shown at *r* (Fig. 5) and in this way it is possible to obtain any size of blow from zero to 1145 lb. It is obvious that for the small customer, this type of hammer will prove much more satisfactory than an ordinary board hammer which is capable of giving only one size of blow for a given length of stroke. This principle has already been made use of during the period it has been in production work. Therefore the electric hammer is more flexible, is handier, cheaper to operate, probably cheaper in first cost; and while the board hammer has the advantages of the flywheel, the electrical hammer has the advantages of the power on the downward stroke.

CONCLUSIONS

To recapitulate, the straight-line motor has proved inefficient for driving railroads, due in part to causes inherent to this type of motors and in part to lack of detailed study relating to the proper construction and to the proper class of railroads to which it should be applied. The motor will, however, prove to be very useful in cases where it is best adapted. The electric hammer is only one of these cases, many others will soon be found and in fact, several of them are already under consideration. I hope in the near future to publish, besides the results of a new hammer now under test, a treatment of this subject under a much broader title in which the electric hammer will appear as a special case of a particular branch of the subject, "The General Motor."

Discussion

R. E. Hellmund: There is in such a hammer air gaps on the two sides of the moving parts. Have any difficulties been experienced, such as bending of the moving parts, or getting excessive friction on one side?

P. Trombetta: We have not experienced any difficulty in that line, and from the fact that they are pretty well balanced, the difficulties, if there should be any, will be minimized almost to nothing by putting the two stators in parallel, in which case as the air gap increases, the current in the one stator in which the air gap increases must increase, in order to keep the voltage the same, and consequently the force is kept almost constant, and there are no difficulties.

Wm. McClellan: How large a hammer have you built and worked?

P. Trombetta: The total moving mass of the hammer is around 275 to 280 pounds.

H. L. Wallau: What is the force of the blow in foot pounds?

P. Trombetta: That can be easily calculated. When you put full power downwards it reaches a speed of about 13.8 feet per second. That squared, times 275, will give you the force of the blow.

A Relay Recorder for Remote Control by Radio

BY F. W. DUNMORE
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Review of the Subject.—*Relays have been used for many years in wire telegraphy and other electrical work. The practical operation of relays actuated by received radio signals is a comparatively recent development, and has been made possible by the development of the electron tube amplifier.*

This paper describes the development and the operating principles of a type of relay recorder which is designed to operate from the output terminals of a radio receiving set and which may also be operated by any other source of audio-frequency signal.

By the use of special electron tube circuits the audio-frequency signal is caused to operate an ordinary telegraph relay.

In order to avoid the necessity for using a very sensitive relay, designed to operate on currents of a milliampere or less, which would have delicate adjustments and light contacts and spring tension, advantage was taken of an electron tube amplifier, which has now become a reliable radio instrument, to increase the input voltage to the relay circuit thus making possible the use of a simple ordinary high-resistance telegraph relay. The relay device has therefore been developed to operate from the output circuit of any suitable amplifier in place of the ordinary telephone receivers.

The operation of the relay may serve to work a sounder, buzzer, tape register or any mechanism for remote control by radio.

Two types are described. One type is designed to be operated from batteries. The other type is designed to operate entirely from any 60-cycle 110-volt lighting circuit and this feature makes this type simple and inexpensive to operate, durable and practical. Another unique feature is described which is that of tuning to different audio-frequencies whereby any one of three signals, each of a different audio pitch, may be caused to operate the relay to the exclusion of the others.

Curves and diagrams are shown illustrating the principles of operation.

By the use of two of these relay recorders connected in series across the output terminals of a single radio receiving set, two messages sent on practically the same wave length but of different audio-frequencies, have been accurately received simultaneously.

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Type A—For Use With Batteries

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2. Requirements. (100 w.)
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4. Principle of Operation. (275 w.)
5. Method of Increasing Sensitivity and Selectivity. (275 w.)
6. Speed of Operation. (75 w.)
7. Sensitivity. (100 w.)
8. Durability. (40 w.)
9. Portability. (25 w.)
10. Uses. (230 w.)
Type B—For Use on the 60-Cycle, 110-Volt, A-C. Supply. (330 w.)

TYPE A— FOR USE WITH BATTERIES

1. *Object of Development.* The object of this investigation was to develop a relay which should operate by received radio signals.

2. *Requirements.* To be satisfactory as a relay recorder the device should have the following characteristics: (1) it must be of simple construction with few adjustments; (2) it must be easy to adjust and capable of being put into operation quickly; (3) it must be selective and as free from static and such disturbances as possible; (4) it must be capable of operating at a speed of at least 12 times per second; (5) it must respond to weak signals; (6) it must be of strong design, durable and capable of maintaining its adjustments; (7) it must be portable.

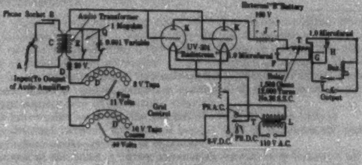

FIG. 1—CIRCUIT DIAGRAM OF RELAY RECORDER FOR USE WITH BATTERIES

3. *Circuit Used.* In order to avoid the use of a very sensitive relay designed to operate on currents of a milliampere or less, with delicate adjustments and light contacts and spring tension, advantage was taken of the radio-audio amplifier (which has now become a reliable radio instrument) to increase the input voltage to the relay circuit, thus making possible the use of a simple ordinary high-resistance telegraph relay. The relay device has therefore been developed to operate from the output circuit of any suitable amplifier in place of the ordinary telephone receivers. The only adjustment necessary is that of an ordinary telegraph relay.

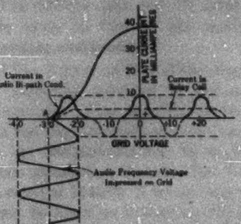

FIG. 2—TUBE CHARACTERTISTIC SHOWING PRINCIPLE OF OPERATION OF RELAY RECORDER

Fig. 1 shows the wiring diagram. *A* is a telephone plug for connecting the relay device to the amplifier output. *B* is a phone socket, so that if desired the operator may listen to the received signal in the ordinary way. *C* is an audio transformer of the type used in audio amplifiers, the type used at present being a Signal Corps Type C-21. *E* is a two-megohm, grid leak.

Presented at the Spring Convention of the A. I. E. E., Chicago, Ill., April 19-21, 1922.

Q is a 0.0006-microfarad variable condenser or 0.0003-microfarad fixed condenser. *D* is a 60-volt variable "C" battery variable in steps of approximately three volts. *J* is a 160-volt dry "B" battery self-contained within the set. *K* is a type *UV*-201 Radiotron. *F* and *H* are each a one-microfarad paper condenser. *T* is an ordinary telegraph relay rewound with 12,000 turns of number 38 S. S. C. enamel wire. *A′* is the output to be connected to the apparatus to be controlled. *L* is a step-down transformer for operating the tube filaments from the 110-volt a-c. supply when such a supply is available.

4. *Principle of Operation.* The principle of operation is illustrated in Fig. 2. By means of the variable "C" battery *D*, the grid voltage is adjusted to approximately 30 volts at which value the plate current is zero, as shown at *A*. The incoming audio-frequency voltage impressed on the grid varies the grid potential, for example, from − 30 to − 20 volts. The 10 volts decrease from − 30 to − 20 causes an increase, for example, from 0 to 10 milliamperes, while the increase from − 30 to − 40 volts is not effective in causing a plate current to flow due to the fact that − 30 volts is already sufficient to reduce the plate current to zero. The result will be a pulsating direct current of 10 milliamperes, maximum amplitude, in the plate circuit. This current, flowing through the plate circuit and condenser *F* causes an increase in the plate current at the keying frequency, which change, passing through the relay coil will pull the relay armature over, making contact at *T*, which contact may control any mechanism desired. With the "C" battery grid voltage adjusted for maximum sensitivity it was found that static induction, etc., operated the relay. When these disturbances are not as strong as the signal their effect on the relay may be overcome as shown in Fig. 3. For example, the "C" battery is shown increased to − 35 volts, the critical value for maximum sensitivity being − 30 volts. The disturbances due to stray currents, etc., merely reduce the "C" battery voltage to − 30 which is not sufficient to cause plate current to flow. However, the signal, being of greater intensity than the stray currents, reduces the voltage to − 25 which causes a plate current of five milliamperes. It will be seen therefore that all disturbing effects, if of less intensity than the signal, do not affect the relay.

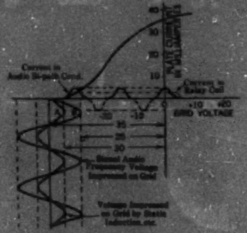

Fig. 3—Method of Elimiating Static and Induction Noises which are not Stronger than the Signal

5. *Method of Increasing Sensitivity and Selectivity.* During the development of this relay it was found that the rectified audio-frequency current in the plate circuit caused the relay armature to chatter rapidly and make a poor contact with the fixed contact point through which the circuit is closed. This was overcome completely, however, by the addition of a one-microfarad condenser across the relay coils. This served the purpose of an audio-frequency by-path for the highly inductive winding of the relay, thus greatly decreasing the resistance of the circuit. The change of plate current due to this audio-frequency caused a second change which occurred at the keying frequency. This latter change passes readily through the relay coils and exerts a strong steady pull on the relay armature without the least chattering.

It was also found that the 0.0006-microfarad variable condenser, Fig. 1, across the secondary of the input audio transformer made possible audio tuning, which increased the selectivity considerable. This tuning was very sharp and it was found that European stations could be made to operate the relay while a high-power station here in the United States would fail to operate it, although the high-power station was coming in on the same wave length and slightly stronger. This was made possible by adjusting the heterodyne note of the European station to a frequency different from that of the local station and then tuning the secondary of the audio transformer to that frequency. The 0.0006-microfarad variable condenser may be replaced by a 0.0003-microfarad fixed condenser and the audio tuning accomplished by adjusting the heterodyne note to the resonant frequency. By means of this audio tuning one of three stations transmitting simultaneously has been selected and caused to operate the relay although all were of equal intensity.

By the use of two relay recorders connected in series across the output terminals of a single radio receiving set, two messages sent on practically the same wave length, but of different audio frequencies, have been accurately received simultaneously.

6. *Speed of Operation.* Tests showed that with a signal strength sufficient to produce a plate current of 10 milliamperes the relay could be operated at a speed of 48 contacts per second, the contact being sufficient to operate a buzzer. With three milliamperes in the plate circuit a speed of 27 contacts per second was obtained. With one milliampere a speed of 19 per second. In each case the relay armature spring tension was adjusted for the best operation.

7. *Sensitivity.* As stated above, this relay was designed primarily with the intention of obtaining a device which should be durable, simple in operation, and strong in construction. Sensitivity is obtained by

means of radio-audio amplification thereby increasing the voltage input to the relay circuit and eliminating the necessity of extreme sensitivity in the relay. Tests at 600 cycles showed that the relay circuit was fairly sensitive, as approximately 1.3 volts at the input terminals of the audio transformer in the relay circuit, caused a current of five milliamperes to flow through the relay coil in the plate circuit.

Fig. 4—Type A Relay Recorder for Use with Batteries

8. *Durability.* As the relay instrument used in this recorder is of the ordinary telegraph type its durability is well established. The only elements requiring occasional renewal are the two electron tubes, the 60-volt "C" battery, and the 160-volt "B" battery.

9. *Portability.* The complete recorder with the exception of the filament lighting battery is contained in a cabinet 7 in. by 13 in. by 11 in., as shown in Fig. 4.

10. *Uses.* 1. As an ordinary receiver it has advantages over reception with telephone receivers, for one may receive by buzzer or sounder with all induction and interfering noises eliminated (if not louder than the signal.)

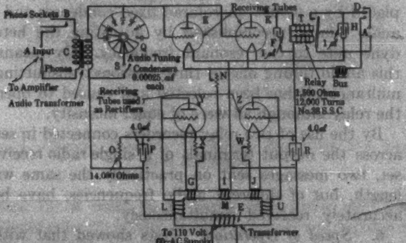

Fig. 5—Circuit Diagram of Relay Recorder for Use on the 110-Volt A-C. Supply

2. A tape or drum-type recorder may be used and a copy made without a trained radio operator.

3. Time signals may be recorded.

4. A call system may be worked by a time switch connected to close the filament circuit for a given time at set calling intervals.

5. Any form of mechanism may be operated by an incoming signal.

6. A receiving station may be located remotely from the transmitting station and the radio signals relayed by wire to the operating room some miles distant.

In conclusion it may be stated that a relay of this type should operate satisfactorily, *without attention*, on an airplane where mechanical vibration may be excessive as the pull on the armature with three milliamperes, or over, in the relay coil makes possible the use of a spring tension on the relay armature sufficient to keep it from moving due to mechanical vibration of the relay.

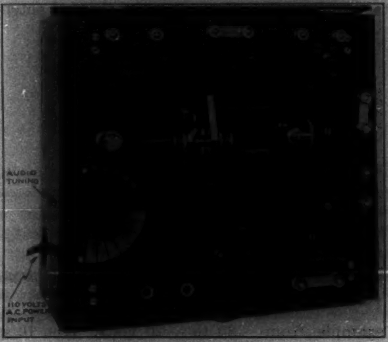

Fig. 6—Type B Relay Recorder for Use on the 110-Volt A-C. Supply

It would seem that the above-mentioned feature makes this remote control relay more serviceable than those now on the market which require delicate adjustment of spring tension, contact points, and suspended vibrating elements.

TYPE B—FOR USE ON THE 60-CYCLE, 110-VOLT, A-C. SUPPLY

This recorder is similar in construction and operation to the Type *A* recorder, except that the plate and grid voltages (B and C battery) are supplied from the 60-cycle, 110-volt a-c. supply. The current for operating the tube filaments is also obtained from this source, so that the recorder is operated entirely independent of any form of batteries. It is only necessary, therefore, to connect to the 110-volt a-c. line and the recorder is ready to operate.

The method of operating the recorder from the a-c. supply consists in the use of the two receiving tubes as rectifiers as shown in Fig. 5. The tubes *Y* and *Z* are used as half wave rectifiers, one supplying the plate voltage, and the other the grid voltage. When used as rectifiers, receiving tubes should have the grids and plates electrically connected together. A special transformer *M* with six windings is used. Two of the windings *G* and *J*, supply the filaments of the two rectifier tubes. A third, *I*, the filaments of the recorder tubes. A fourth, *U*, the high voltage for the plate. The fifth, *L*, supplies the grid voltage, and the sixth, *E*, is the 110-volt primary winding. The rectified alternating current is smoothed out by means of four microfarad condensers *P* and *R*, connected across the output terminals. As the currents in the grid and plate circuits are small, smoothing out inductance was found unnecessary. It was found necessary to put 40,000 ohms as shown at *O*, across the output circuit of the rectifier tube supplying the voltage to the grid, as the grid is otherwise insulated from the filament of tubes *K* by the rectifier tube. By means of the filament rheostats, *X* and *W*, the grid and plate voltages may be varied over any ranges desirable for the most efficient operation of the recorder. By the use of binding posts with straps as shown in Fig. 6, the type *B* recorder may be operated from *A*, *B* and *C* batteries for supplying the filament, plate and grid voltages respectively in cases where the a-c. supply is not available.

In cases where very high-speed operation is desired, the ordinary relay may be replaced by one designed for high-speed operation.

Discussion

Wm. McClellan: Is it practical, may I ask, to use that device for the tripping of relays in connection with circuit breakers?

E. E. F. Creighton: I am not sure from the author's remarks whether he used two frequencies, a fundamental and then a note frequency in addition to that, in order to prevent accidental operation. Suppose this device were used to operate a distant oil circuit breaker, what would be the chances of its operating through picking up some wireless wave.

Allan C. Forbes: I think that Mr. Dunmore has a very clever device; the possibilities of which are unlimited, due especially to the fact that it is more compact than any relay that I have yet seen. I happen to have had a great deal of experience in a high power station for the Marconi Company, having done the first testing between San Francisco, Honolulu and Japan; also between Marion, Mass. and Stavanger, Norway, and I have seen a great many recorders, I have worked on them personally and this is the first really successful thing that I have seen that is efficient and yet simple,—plug it into the light socket and let it go.

Mr. Schraeber: The author has explained that you might control a ship or airplane in this way, and he has also explained that he is able to get very close tuning, it being possible to tune both to the audio frequency and to the radio frequency. Having adjusted his device, I would like to know whether he has had any particular experience toward the end of always being able to send out the proper wave, either audio or radio, so that the device in which there is no individual to do the tuning will surely respond to those impulses. Can you set it and leave it perhaps for a day or so at some distant point and then start up a signal which will be closely tuned to it.

Allan C. Forbes: I tried out a device in Bolinas, Cal. (Marion Co.), the 300-kv-a. Radio Station of the M. W. T. Co. of America, while there as dynamo tender, and later on as engineer. We had a schedule of starting up at 10:00 o'clock in the morning to work Honolulu until 2:00 p. m. and then shut down; then start up again maybe at 4:00 or 5:00 o'clock and send what few messages we had. Then we would shut down until 9:00 o'clock at night and then get rid of all the business from 9:00 o'clock until 12:00. This was in 1915-16.

Now there would come long stretches, during good reception, when we could afford to shut down, possibly for an hour. Then the operator would want power quickly. We had induction motors, and all automatic starting; it would take us about sixty seconds to start up. Well, I thought out a great many plans whereby I wouldn't have to get out of my soft box. So I rigged up a relay device, unbeknown to the Marconi Wireless Telegraph Co. of America. I had it fixed so that I kept current on the circuit through the relay, and all the operator had to do was to touch his sending key, that tripped the circuit which threw in the automatic starter and started the main motor-generator set with the main motor generator on the way to going up, all I had to do then was to tell the dynamo tender to start the air compressors and open the valves and we were all ready.

We used a grounded circuit, several amateurs in and around San Rafael had one kw. stations. They were not careful as to their antenna and they used a great deal of power. The relays we used were very sensitive, so much so that one time the whole station was put into operation, and when I got it all going I didn't hear any signaling going over it, so I called up the operator and he said, "No, I didn't ring for the juice." I shut down, and shortly thereafter I started up the same way again. So I disconnected it and sat over by the relays and I could read all the signals that the amateur was sending out from San Rafael. Our line was at right angles to San Rafael, and San Rafael was over twenty miles away. We could have provided against that if we had had Mr. Dunmore's relay with his audio tuning device.

D. D. Clarke: I am connected with an operating company and a device of this kind appeals to us as one that could be put on an auto or truck and enables us to reach the trouble man at all times, without the necessity of his keeping his head set on.

Victor E. Thelin: In connection with the possibilities of this relay controlled by radio, I have been thinking of one thing which no doubt is of interest to you engineers, as many of you no doubt are power engineers, whose work brings you in touch with the furnishing of power from rotary converter and motor-generator substations. Large metropolitan systems, of which the Chicago Surface Lines is typical, heretofore have been fed from multi-unit substations, the capacity of which range from 4000 to as high as 20,000 kw. While complete shutdowns due to trouble on the high-tension system do not happen very often now, due to the fact that practically all of the high-tension lines are equipped with reverse-power relays, which isolate a defective line, yet there are times when quite a number of substations are shut down, and it is necessary, in order to restore service, to open sufficient feeder switches to reduce the load on the feeder bus to the amount capable of being picked up by one rotary, and then as additional rotaries are connected to the station bus more of these feeder switches are closed .

If the large substations in the residential districts and in the outskirts of the city were separated into a number of automatically controlled single-unit substations or, at the most, two-unit substations, it might be possible to have same so arranged that a load despatcher could have complete control of same, through the use of a radio controlled relay which might enable him to connect all of the stations to the system simultaneously. Furthermore, in case of a shutdown on a low-tension d-c. lighting system, such as is used by the Commonwealth Edison Company in Chicago, it is necessary to have a great reserve capacity in storage batteries in order to restore service, as it is impossible without these batteries for any one rotary converter substation to be connected to the distribution system, due to the fact that this distribution system is one solid network, and the first substation in operation would open up on overload. It might be possible to have all the rotaries in both manually and automatically operated substations running ready for service, and the actual connecting of same to the distribution system could be done simultaneously by a load dispatcher through the use of the radio relay described here today. There is one point, however, on which I am not clear, as I have not as yet become a "wireless bug" and that is as to whether or not it would be possible to arrange these relays so that they could be operated independently of all the others in regular service and yet all be closed simultaneously in case necessity so demanded.

H. L. Wallau: There is a possibility of having one or more of these devices to perform different functions in the remotely controlled wireless substation, and I should like to know whether there would be any great difficulty in establishing a code of audio signals that could be easily transmitted from some central point.

F. W. Dunmore: I have, in developing this relay, merely developed it as a mechanism to be operated by radio, having left the finer details of selectivity by means of group signals to someone else who may design a ratchet mechanism that would be operated by this relay. The air service is doing work along this line and has actually obtained results. You have probably read of their radio controlled auto which they have been steering through the streets of Dayton, Ohio, maneuvering it right and left and starting and stopping it and blowing the horn. That has all been done, first, through a relay, and secondly by means of a series of signals properly spaced, and of suitable length, operating a selectivity mechanism, mechanically selective, which, in turn, gives the different controls. These methods for obtaining selectivity, may be used for the control of oil circuit breakers in order to prevent them from being operated by any other signal.

I remember reading recently in one of the radio magazines an article which stated that there had been developed a relay, which performed a similar function to that of mine, but was so fixed mechanically, by certain ratchet mechanism, that it would respond only to three dots, three long dashes, and three more dots (the distress signal). This could be put on a ship without an operator and would ring a bell whenever a ship sent a distress signal.

I cite the above merely to show it is possible to make a relay doubly selective, not only electrically selective by radio, both to radio frequency and audio frequency, but also mechanically selective to the extent that it will not operate a control switch or a signal bell unless a certain number of signals are received in a given time and suitably spaced. A somewhat similar method was used by the air service in the control of the auto in Dayton.

There is another method of obtaining mechanical selective control with which I am familiar, but which I cannot go into now, whereby any number of controls could be made. It is very flexible, making possible 25 or more different controls.

I believe the foregoing will answer the first two questions. In the development of my relay no attempt was made to obtain mechanical selectivity.

As for keeping an enemy from operating the relay, this could be taken care of by the use of a combination of electrical and mechanical selectivity. The code could be deciphered in time but the relay may be constructed so as to operate on a number of different codes.

As for leaving the relay at a substation without an attendant, there is always the danger of a tube burning out, but as the life of a tube is several months, this danger is remote. The control signal could be sent from a given point, and on a given wave length, and be of such character that it would operate the mechanically selective mechanism, which in turn would open or close the circuit breakers.

By utilizing electrical and mechanical selective features, it should be possible to keep an interfering station from operating the relay mechanism.

Regarding the use of the relay on trucks in order to call linemen, it would be simpler to use a radio receiving set without the recorder. This would not require as much mechanism. If the truck were in motion, the relay could be used to make a visual indication or call.

The relay was developed primarily for use on airplanes, and for this reason was designed to operate on a signal of sufficient strength to give positive action. For use on an airplane a relay should be very rugged and simple, with no delicate adjustments of spring tension and relay contacts or suspending elements. In my type of relay the spring tension can be made considerable, thus pulling the armature back so that vibrations on the plane will not move it until the signal is received. The ignition noise is picked up by the radio receiving set, in some cases just as I received it here from that commutator, and in cases where it is very loud it might operate the recorder. It is possible to shield the ignition systems on airplane engines so as to reduce the noise from the ignition to a minimum. If this interference is not stronger than the received signal, it will not operate the recorder. Thus the relay may be readily used for visual indication on a plane, as the noise is so great from the roar of the engine that it is hard to read a signal by ear.

As for controlling a number of substations by means of one central radio transmitting station, this may be done by sending a signal of a given wave-length and character as I have previously mentioned. Each substation should have a radio receiving set in operation ready to receive the signal. This would mean that the filaments of the tubes would have to be lit, so that the radio receiving set would be ready to function, and thereby operate the relay.

Mr. P. D. Lowell and I have recently developed at the Bureau of Standards a radio receiving set that operates entirely from the a-c. power line. It consists of six stages of amplification. This might be used in conjunction with the recorder on the a-c. supply.

Some very interesting questions have been asked by Mr. Varley of New York, some of which might interest you. He inquired why twenty volts are necessary to reduce the plate current to zero. I am using such a high plate voltage that it requires a large grid voltage to reduce the plate current to zero. Mr. Varley stated that three volts should be sufficient. Three volts would be all right with a plate voltage of 20 volts; I have 200 volts, so I must have a correspondingly higher grid voltage. The use of a-c. does not affect the operation of the recorder. When the relay is adjusted for maximum sensitivity, with a spring tension so that the armature is just about to make contact, there is a slight 60-cycle chatter of the armature but is not objectionable because the relay is never operated in that condition.

Mr. Varley also asks why 4000 ohms were used across the condenser in smoothing out. It should be 40,000 ohms. It serves as a grid leak and keeps the grids from being insulated from the rest of the circuit. A receiving tube cannot be operated with the grids insulated from the filament.

Magnetic Flux Distribution in Transformers

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It is customary when discussing magnetic leakage in the transformer to consider the primary and secondary windings as having a counter e. m. f. induced by a flux surrounding the coil and having the core for a part of its path. This leakage flux is frequently represented by closed lines.

Since the main flux is also represented by closed lines in the core, apparently two fluxes are to be found in the core under a given coil, namely, the leakage flux and the main flux.

The main flux is the flux found in the core at a point not under either the primary or secondary winding, and has been commonly considered as being the flux which causes the secondary induced voltage.

If the leakage fluxes have a separate existence, i. e., if they are to be represented by closed lines, then the flux along the edges of the core would consist largely of leakage lines while that to be found in the middle portion of the core would be the main flux. Since these fluxes are out of phase with one another it should be possible to identify them if they are present as separate fluxes.

Using a simple test core-type transformer, provided with belt exploring coils under both the primary and secondary windings, data concerning the magnitudes and phase positions of the fluxes in different sections of the core were secured.

The results show that leakage fluxes do not exist as separate fluxes in the core. It is also shown that the primary and secondary induced voltages are equal to the primary and secondary terminal voltages diminished and increased respectively by the corresponding I R drops.

Some difference of opinion exists among engineers concerning the distribution of lines of magnet flux in a transformer operating under load. Many and in fact practically all of the text-books, in the writers, treatment of the transformer, divide the so-called leakage reactance into two parts, one part being due to the primary ampere turns, and the other to the secondary ampere turns. This notion of the leakage reactance assumes that a secondary leakage flux exists, and in many cases is taken as being equal to the leakage flux of the primary. Others believe that the leakage flux actually to be found in a transformer is the result of the combination of primary and secondary m. m. fs. rather than a combination of the fluxes produced by each m. m. f. acting separately.

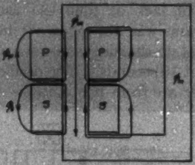


FIG. 1

ϕ_m = main flux.
ϕ_p = primary leakage flux.
ϕ_s = secondary leakage flux.

OBJECT OF THE PAPER

In order that the experimental evidence might be secured, a small transformer was built up, and the flux distribution studied. It is the purpose of this paper to describe this investigation, and point out some conclusions which may be drawn from the results obtained.

EXPERIMENTAL APPARATUS: THE TRANSFORMER, INSTRUMENTS AND GENERATOR

By reference to Figs. 1 and 2, which are drawn in accordance with the two theories outlined above, it will be seen that the difference in the flux distribution is to be found in the space underneath the secondary coil. The flux under the primary coil is the same according to either theory.

In order that the flux and its phase relations might be determined, it was decided to make use of belt coils similar to those described by Kennelly and Alger in their paper on "Magnetic Flux Distribution in Annular Steel Laminae" before the Institute in 1917. The simple type of transformer shown in Figs. 1 and 2 was chosen, and belt coils were threaded through holes bored in the core underneath the primary and secondary coils.

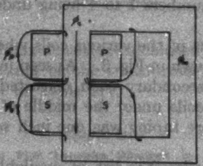


FIG. 2

ϕ_t = flux which threads both primary and secondary.
ϕ_s' = flux which threads primary, but which passes outside secondary.
ϕ_p' = flux which threads primary only.

The core was built up out of straight laminations 8 in. (20.3 cm.) long, 2 in. (5.08 cm.) in width, and having a thickness of 0.014 in. (0.455 mm.). These laminations were cut from a good grade of silicon transformer steel. The punchings were all carefully annealed after cutting, and the oxide thus formed was depended upon to furnish sufficient insulation between sheets. The core data are given herewith.

Presented at the Spring Convention of the A. I. E. E., Chicago, Ill., April 19-21, 1922.

Number of laminations...... = 128
Depth of core............... = 1.875 in. (4.76 cm.)
Thickness of lamination..... = 0.014 in. (0.355 mm.)
Cross-section of core........ = 3.375 sq. in. (21.7 sq. cm.)
Stacking factor............. = 0.9
Weight of core.............. = 24.2 lb. (10.52 kg.)
Number of air gaps.......... = 4

Six holes, 0.154 in. (0.391 cm.) in diameter, were drilled through the core in the locations shown in Fig. 3. They were carefully reamed out to size, all burrs removed, and the surfaces painted with shellac. Through these holes, 40 turns of No. 34 B & S enameled wire were wound, forming altogether eight belt coils, with 80 wires per hole. The belt coils were numbered from 1 to 8, numbers 1 to 4 being under the primary coil.

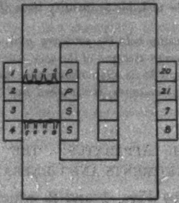


FIG. 3

Core area diminished by the area of the belt coil holes = 2.9 sq. in. (16.7 sq. cm.)

All transformer coils have 200 turns each, and are wound with No. 16 B and S wire.

Coils 7 and 8 were used as tertiary coils. Coils 20 and 21 were not used in this investigation.

Resistances of transformer coils at 25 deg. cent:
(1) = 0.772 ohm (4) = 0.769 ohm
(2) = 0.767 " (7) = 0.775 "
(3) = 0.771 " (8) = 0.782 "

Belt coil area $(\text{cm.})^2$:
(1) 4.59 (5) 4.43
(2) 3.80 (6) 3.77
(3) 3.74 (7) 3.81
(4) 4.67 (8) 4.76

The positions of the various coils when placed upon the core are shown in Fig. 3. As seen in the figure, the primary and secondary each consisted of two coils, with the belt coils under the middle of each winding. Each coil before taping was one inch square in cross-section.

After canvassing the list of available instruments, it was decided to connect a low-reading milliammeter in series with the belt coil under test and a sensitive element on the oscillograph. The ammeter has a full-scale deflection of 0.030 ampere, a reactance of from 0.25 to 0.27 henry and a resistance of 304.5 ohms. To prevent the current through the belt coil in use from distorting the flux, it was necessary to provide a similar load for each of the three belt coils not under test. To do this three coils were each wound to an inductance of 0.25 henry and a resistance of 300 ohms. The winding data for these coils were obtained from the curves given by Brooks in Bulletin 53, University of Illinois, Engineering Experiment Station.

To make changes in connections easily and quickly, the three loading coils and the test circuit were connected to telephone plugs as shown in Fig. 4.

An alternator rated at 7.5 kv-a., 110 volts, 60 cycles, furnished practically a sine wave for the test.

METHOD OF TEST AND RESULTS

Tests were made with the transformer operating under the following conditions:

(a) No-load.

(b) Secondary short-circuited, with impedance volts supplied to the primary.

(c) Non-inductive load.

(d) Inductive load.

A magnetization curve was taken, and a point chosen on it below the knee of the curve so that the exciting current would not show distortion due to changes in permeability.

Oscillograms showing the phase relation of the belt coil current and the impressed voltage were taken. The voltage wave, designated by the letter *e* on the oscillograms, was used as a reference for determining the position of the current flowing through the particular belt coil under test. In each case while the current in one belt coil was being investigated, the other three belt coils were connected to their respective loading coils.

On account of lack of time the usual method of taking oscillograms was not followed; instead bromide paper was placed on the viewing screen and exposed for a period of about 10 seconds. The oscillograms appearing in this paper are from photographs of these prints.

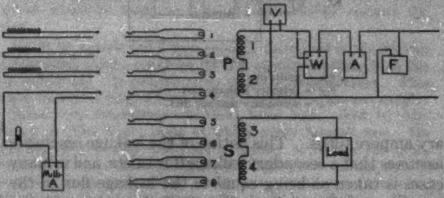


FIG. 4

Using the belt coil ammeter readings, and the constants of the ammeter circuit, the voltage induced in each belt coil was calculated. From these voltages the fluxes linking the various belt coils were obtained.

Using the calculations given in the appendix based upon the no-load and impedance test data, the phase positions and magnitudes of the various voltages were calculated. The data obtained from the belt coils are compared in each case with the results obtained by calculation.

The vector diagrams are drawn to scale using the calculated data.

(*a*) *No-Load Conditions.* Core loss test data: 115 volts, 0.08 ampere, 2.47 watts, 61-cycle frequency.

TABLE I.

Results of Tests Made Under No-Load Conditions.

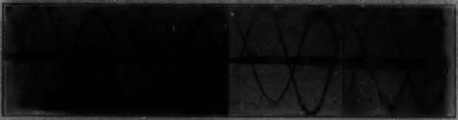
Belt Coil No.	Belt Coil Amperes	Flux per sq. cm. (B'_{max})	Degrees Displacement	Average B'_{max}	Average Angle
I	II	III	IV	V	VI
1	0.0086	5680	40		
2	0.0084	6690	40	6230	37 lag
3	0.0086	6950	35		
4	0.0088	5600	32		
5	0.00835	5640	35		
6	0.00835	6610	33	6070	33 lag
7	0.0085	6640	33		
8	0.0086	5390	32		

Fluxes in column (III) are calculated from column (II) and show the maximum value of flux threading the belt coil turns.

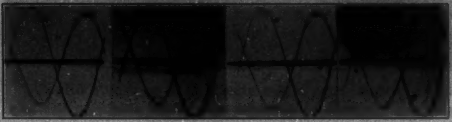
Angles in column (IV) are taken from the oscillograms, and have been diminished by 180 degrees since an applied voltage rather than an induced voltage was used as a reference.

The flux density corresponding to the impressed voltage (115) is 6240 lines.

The lag angles shown in Table I show but little variation, and an angle of 33 degrees will, therefore, be subtracted from the angles measured on the oscillograms. This correction when applied to the position of the belt coil current wave, should give the approximate location of the voltage induced in the belt coil winding.



Primary Belt Coils



Secondary Belt Coils

FIG. 5—NO-LOAD CONDITIONS—SHOWING POSITIONS OF BELT COIL CURRENTS

e = reference voltage

The flux density given by the table is seen to be greater in the middle of the core than on either side. This condition is true for both the primary and secondary, the primary being slightly greater in value.

It will be noticed in all the following tests, that the flux distributes itself across the core in about the same manner no matter what the condition of loading may be.

(*b*) *Impedance Conditions.* (*Secondary Short-Circuited.*) Test data: Impedance volts (E_p) = 60 volts, primary current (I_p) = 4 amperes, input watts (W_p) = 51.3 watts, tertiary volts (E_m) = 24 volts, frequency (f) = 60 cycles.

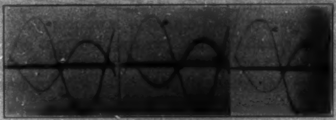
TABLE II.

Results of Belt Coil Tests Made Under Impedance Conditions.

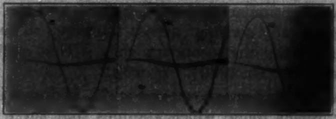
Belt Coil No.	Belt Coil Amperes	B'_{max}	Degrees Displacement	Corrected Angle	Average B'_{max}	Average Angle
I	II	III	IV	V	VI	VII
1	0.0046	3040	24 lag	9 lead		
2	0.0045	3580	22 "	11 "	3330	8 lead
3	0.0045	3640	27 "	6 "		
4	..	..	..	..		
5	..	310*	98 lag	65 lag		
6	..	370*	98 "	65 "	340	66 lag
7	..	370*	100 "	67 "		
8	..	..	..	..		

Angles in column (V) are equal to those in column (IV) diminished by 33 degrees.

*These fluxes were calculated from the amplitude of the current wave, the oscillograph element having been previously calibrated.



Primary Belt Coils



Secondary Belt Coils

FIG. 6—IMPEDANCE CONDITIONS—SHOWING POSITIONS AND MAGNITUDES OF BELT COIL CURRENTS

e = reference voltage.

Voltages and flux densities, calculated (see appendix) from the constants of the transformer, and the test data, are given in Table III.

TABLE III.

Voltages and Flux Densities Obtained by Calculation. (Impedance Conditions)

Voltage	B_{max}	B'_{max}	Degrees Displacement
I	II	III	IV
$\overline{E}_p = 60 + j0$			
$\overline{E}_p' = 58.7 + j6.0$	2530	3290	6 lead
$\overline{E}_m = 23.9 - j1.6$	1030	1470	4 lag
$\overline{E}_s' = -1.32 + j6.1$	260	340	76 lag
$\overline{E}_s = 0.0 + j0.0$			

$\overline{E}_p$ = primary impressed voltage. $\overline{E}_p' = \overline{E}_p$ diminished by $\overline{I_p R_p}$.

$\overline{E}_m$ = voltage induced by main flux, i. e., flux in parts of the core not under either primary or secondary coils.

$\overline{E}_s$ = secondary terminal voltage. $\overline{E}_s' = \overline{E}_s$ increased by $\overline{I_s R_s}$.

B_{max} = normal flux density in the core.

B'_{max} = normal flux density in the core based on undiminished cross-section of core.

From a comparison of the flux densities and angles shown in columns VI and VII of Table II with the corresponding values in columns III and IV of Table III, it is clear that the voltage induced in the primary is $\overline{E}_p'$ and that the secondary induced voltage is $\overline{E}_s'$. $\overline{E}_m$ has been commonly referred to as the voltage induced in the secondary winding, but the data show that the flux found under the secondary winding is only sufficient to induce a voltage equal to the secondary *I R* drop.

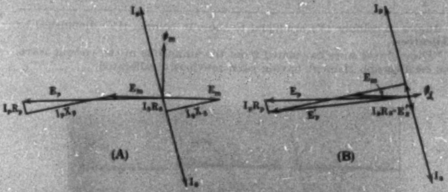


Fig. 7

No trace of the leakage flux is found in the core under the secondary as a separate flux, the distribution across the core being similar to that at no-load, and the angle of lag practically constant across the core. The only flux found under the secondary coils is that sufficient to overcome the secondary *I R* drop.

The vector diagram shown in Fig. 7A, is drawn in the manner usually found which assumes that there is an actual reactance drop in both primary and secondary, and that the induced voltage is equal to E_m. Another diagram based upon the idea that the induced voltages are those found in this test is shown in Fig. 7B.

Either method will give the same numerical results, but it is to be remembered that the leakage flux and the main flux cannot exist in the core as separate and independent fluxes. Further discussion of the two methods will be found later in this paper.

(*c*) *Non-Inductive Load.* Test data: $E_p = 115$ volts, $I_p = 3.82$ amperes, frequency = 60 cycles.

TABLE IV.

Results of Belt Coil Tests Made with Non-Inductive Load

Belt Coil No.	Belt Coil Amperes	B'_{max}	Degrees Displacement	Corrected Angle	Average B'_{max}	Average Angle
I	II	III	IV	V	VI	VII
1	0.0082	5400	18 lag	15 lead		
2	0.0080	6380	18 "	15 "	6020	14 lead
3	0.0080	6500	20 "	13 "		
4	0.0085	5500	20 "	13 "		
5	0.0067	4600	54 lag	21 lag		
6	0.0068	5460	54 "	21 "	5050	20 lag
7	0.0069	5500	52 "	19 "		
8	0.0070	4450	51 "	18 "		

TABLE V.

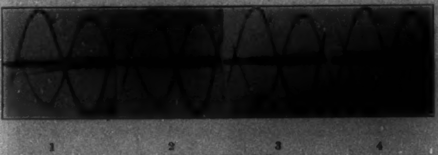
Voltages and Flux Densities Obtained by Calculation (Non-Inductive Load)

Voltage	B_{max}	B'_{max}	Degrees Displacement
I	II	III	IV
$E_p = 115 + j\,0$			
$E_p' = 109.8 + j\,2.86$	4800	6240	1 lead
$E_m = 93.3 - j\,26.8$	4240	5510	16 lag
$E_s' = -82.7 + j\,46.0$	4120	5360	29 lag
$E_s = -77.4 + j\,43.2$			

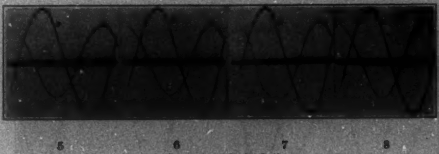
A comparison of Tables IV and V shows that the voltage induced by the flux under the primary corresponds to E_p' while the flux under the secondary induces a voltage of E_s'. While the numerical values do not check as closely as might be desired, yet they are sufficiently close to lead to the conclusion given.

(*d*) *Inductive Load.* Test data: $E_p = 115$ volts, $I_p = 4.03$ amperes, frequency = 60 cycles.

Load characteristics: $E_s = 54$ volts, $I_s = 4.04$ amperes, $W_{load} = 50.6$ watts.



Primary Belt Coils



Secondary Belt Coils

Fig. 8—Non-Inductive Load—Showing Positions of Belt Coil Currents

e = reference voltage

TABLE VI.

Results of Belt Coil Tests (Inductive Load)

Belt Coil No.	Belt Coil Amperes	B'_{max}	Degrees Displacement	Corrected Angle	Average B'_{max}	Average Angle
I	II	III	IV	V	VI	VII
1	0.0087	5740	20 lag	13 lead		
2	0.0083	6620	20 "	13 "	6250	13 lead
3	0.0081	6580	..	..		
4	0.0088	5700	..	..		
5	0.0040	2750	29 lag	4 lead		
6	0.0040	3210	29 "	4 "	2950	3 lead
7	0.0040	3160	31 "	2 "		
8	0.0040	2530	31 "	2 "		

TABLE VII

Voltages and Flux Densities Obtained by Calculation (Inductive Load)

Voltage	B_{max}	B'_{max}	Degrees Displacement
I	II	III	IV
$E_p = 115 + j\,0$			
$E_p' = 113.6 + j\,6.11$	4870	6330	3 lead
$E_m = 78.4 - j\,1.88$	3360	4370	1 lag
$E_s' = -55.6 + j\,6.96$	2390	3110	7 lag
$E_s = -54.2 + j\,0.86$			

DISCUSSION

The flux threading the belt coils was found in every case to be sinusoidal. The reluctance of the four air gaps in the core effectively prevented the distortion noted by Kennelly and Alger in their paper previously referred to.

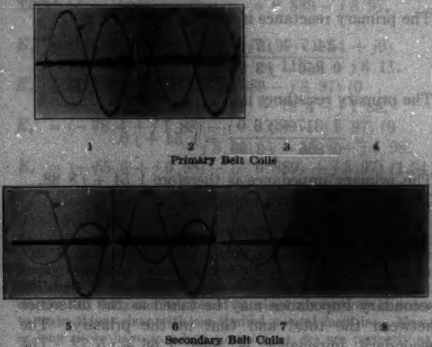


FIG. 9—INDUCTIVE LOAD—SHOWING POSITIONS OF BELT COIL CURRENTS

e = reference voltage.

All the evidence of the tests made goes to prove that the voltage induced in the primary winding is the supplied voltage diminished vectorially by the primary *I R* drop, and that the voltage induced in the secondary winding is equal to the secondary terminal voltage increased vectorially by the secondary *I R* drop. The flux usually referred to as the main flux, and so called in this paper, does not alone produce the induced voltage in either the primary or secondary.

Practically all of the flux found in the ordinary low-voltage transformer, as for example the type generally used for distribution, is produced by the ampere turns of the primary. The ampere turns of the secondary modify the flux produced by the primary, but do not produce any flux which enters the core. The secondary winding may produce flux which does not enter the core, and this will be the case with the higher voltage coils where the distance between coils and core becomes quite large.

It would seem, in view of the fact that the leakage fluxes do not have a separate and independent existence in the core, that it is better not to represent such fluxes by closed lines in the core, because the use of the line conveys the idea that the leakage flux occupies a place close to the edge of the core, thus crowding the main flux to the middle of the core. The conception of lines of force is merely for convenience, and in cases where two or more m. m. fs. not in the same phase are acting upon a common part of the core, an altogether wrong conclusion may be arrived at, if the idea of lines is adhered to closely.

A figure (Fig. 10) suggested to the writer by Prof. Alfred Still, of Purdue University, will perhaps serve to make the presentation of what occurs in the core more accurate than the diagrams as usually drawn. The main flux is represented by three arrows showing the direction of the m. m. f. of the primary winding. Under the primary winding four arrows are found, indicating that the primary leakage flux is out of phase with the three arrows representing the main flux. This flux, and in fact all of the fluxes in the core may be considered as spreading across the core in the same manner as when no current is flowing in the secondary winding. Under the secondary winding the flux indicated by the two arrows is the vectorial difference of the four arrows under the primary, and the four arrows representing the leakage.

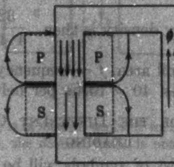


FIG. 10

The calculation of the leakage paths has always nelgected the path in the iron, and since the air paths shown in the figure have not been changed, the method of calculation and the numerical results obtained therefrom are not affected by this investigation.

CONCLUSION AND SUMMARY

This investigation has shown that for the simple type of transformer investigated the leakage fluxes are not to be found as separate fluxes under the primary and secondary coils. Thus the method of representing the leakage fluxes so commonly used in text-books dealing with transformers in which the leakage fluxes are represented by lines in the same part of the core with other lines out of phase with them, does not picture a condition which actually exists.

It has also been shown that the voltage induced in the primary winding is equal to the supplied e. m. f. diminished by the *I R* drop, and that the secondary induced voltage is equal to the secondary terminal voltage increased by the secondary $I\,R$ drop.

The writer wishes to express his appreciation to the members of the Staff of the School of Electrical Engineering at Purdue University, who have taken a lively interest in the matter and who have offered many suggestions of value. Especial thanks are due to Prof. Alfred Still, who has followed the work closely, and under whose general supervision the thesis,[1] of which this is an abstract, was conducted.

Appendix

CALCULATION OF FLUXES FROM BELT COIL AMMETER READINGS

Measured inductance of ammeter = 0.25 henry.

Resistance of circuit including ammeter, belt coil, oscillograph and connections = 311 ohms.

Then $\sqrt{\overline{(311)}^2 + \overline{(377)\,(0.25)}^2} = 325$ ohms impedance at 60 cycles.

The e. m. f. induced is:

$$4.4\, f\, N\, \phi\, 10^{-8} \text{ and equals } 325\, I,$$

The maximum flux density is then $\dfrac{325\, I\, 10^8}{4.4\, A + 40}$

where A = belt coil area, f = frequency, I = belt coil current in amperes, 40 = turns per belt coil.

CALCULATIONS FOR THE DIFFERENT CONDITIONS OF LOADING

The following list of symbols will be used.

E_p = Voltage impressed on the primary.
E_p' = Voltage induced in the primary winding.
E_m = Voltage induced by the main flux in the tertiary coil.
E_s = Secondary terminal voltage.
E_s' = Voltage induced in the secondary winding.
I_p = Primary current.
I_s = Secondary current.
W_p = Watts input to primary.
W_{load} = Watts output of secondary.

Test (b) Impedance Conditions: Calculation of E_m. Test data: $E_p = 60$, $I_p = 4$, $E_s = 0$, $E_m = 24$, $W_p = 51.3$.

Let $E_m = e + j\,e'$. Assuming that $E_p = 60 + j\,0$ then the primary current $I_p = 4\ (0.214 - j\,0.976) = 0.856 - j\,3.9$.

The voltage usually called the primary $I\,X$ drop may be represented by $a\,(0.976 + j\,0.214)$, where a is its real value in volts.

The primary $I\,R = 1.54\,(0.856 - j\,3.9) = 1.317 - j\,6.0$

Then $E_p' = (60 + j\,O) - (1.317 - j\,6.0)$
$= 58.68 + j\,6.0.$

Also $(e + j\,e') + a\,(0.976 + j\,0.214)$
$= 58.68 + j\,6.0$

and $(0.976\,a + e) + j\,(0.214\,a + e')$
$= 58.68 + j\,6.0$

These are identically equal, and therefore,

$0.976\,a + e = 58.68$, and $0.214\,a + e' = 6.0$ also, (1)

$\sqrt{e^2 + e'^2} = 24$, since from the data, $E_m = 24$. (2)

Eliminating a between the equations in (1), substituting in (2) and solving for e' we have

$$e' = 11.36 \text{ or } -1.60.$$

From the vector diagram it may be seen that -1.60 is the correct value. Substituting this value in equation (2) and solving we obtain,

$$e = 23.95.$$

$$\text{Thus}\quad E_m = 23.95 - j\,1.60.$$

Primary I X. For use in the following calculations it will be useful to find value and phase position of the primary $I\,X$:

It is $(58.68 + j\,6.0) - (23.95 - j\,1.6) = 34.73 + j\,7.6.$

The primary reactance is then

$$\frac{34.7 + j\,7.6}{0.856 - j\,3.90} = 0 + j\,8.88$$

The primary resistance is

$$= \frac{1.317 - j\,6.0}{0.856 - j\,3.90} = 1.54 + j\,0.$$

The primary impedance is therefore $1.54 + j\,8.88$. The total transformer impedance is then

$$\frac{60 + j\,0}{0.856 - j\,3.90} = 3.2 + j\,14.6 \qquad (3)$$

Since the ratio of the transformer is 1 to 1, the secondary impedance may be taken as the difference between the total and that in the primary. The secondary impedance is then $1.66 + j\,5.72$. The measured value of the secondary resistance was 1.54.

This check is quite satisfactory when it is remembered that the value of R depends upon the wattmeter reading. The fact that the core loss was neglected tends to make the resistance come out higher than it should. The secondary impedance will therefore, be taken as $1.54 + j\,5.72$.

Then $E_s' = (-\,23.95 + j\,1.60) - (0.855 - j\,3.9)\,(1.54 + j\,5.72) = 1.32 + j\,6.1.$

Test (c) Non-Inductive Load. Test data: $E_p = 115$, $I_p = 3.82$.

Let $E_p = 115 + j\,0$.

Using (3) we have,

$$I_p = 3.82 = \frac{115}{\sqrt{R^2 + (14.6)^2}} \text{ or } R = 26.4 \text{ ohms.}$$

then

$$I_p = \frac{115 + j\,0}{26.4 + j\,14.6} = 3.35 - j\,1.86.$$

$$E_p' = (115 + j\,0) - (1.54 + j\,0)\,(3.35 - j\,1.86) = 109.8 + j\,2.86.$$

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[1] Graduate Thesis, "Investigation of Leakage Fluxes in Transformers," by K. B. McEachron, Purdue University, 1920.

$$E_m = (109.8 + j\,2.86) - (O + j\,8.88)\,(3.35 - j\,1.86) = 93.3 - j\,26.84.$$

$$E_s' = (-\,93.3 + j\,26.84) - (O + j\,5.72)\,(-\,3.35 + j\,1.86) = -\,82.68 + j\,46.0.$$

$$E_s = (-\,82.68 + j\,46.0) - (1.54 + j\,O)\,(-\,3.35 + j\,1.86) = -\,77.5 + j\,43.14.$$

The voltage E_s will be found to be in phase with the secondary current.

Test (*d*) *Inductive Load*. Test data: $E_p = 115$, $I_p = 4.03$, $E_s = 54$, $I_s = 4.04$, $W_{load} = 50.6$.

The resistance and reactance of the load respectively, are:

$$R_l = \frac{50.6}{(4.03)^2} = 3.1 \text{ and } X_l = \sqrt{\left(\frac{54}{4.03}\right)^2 - 3.1^2} = 13$$

Total resistance including load $= 3.08 + 3.1 = 6.18$.
Total reactance including load $= 14.6 + 13.0 = 27.6$

$$\text{Total} \quad I_p = \frac{115 + j0}{6.18 + j\,27.6} = 0.889 - j\,3.97.$$

$$E_p' = (115 + j\,0) - (0.889 - j\,3.97)\,(1.54 + j0) = 113.6 + j\,6.11.$$

$$E_m = (113.6 + j\,6.11) - (0.889 - j\,3.97)\,(0 + j\,8.88) = 78.4 - j\,1.88.$$

$$E_s' = (-\,78.4 + j\,1.88) - (-\,0.889 + j\,3.97)\,(0 + j\,5.72) = -\,55.6 + j\,6.98.$$

$$E_s = (-\,55.6 + j\,6.98) - (-\,0.889) + j\,3.97)\,(1.54 + j\,0) = -\,54.2 + j\,0.86.$$

Discussion

R. E. Hellmund: The points brought out in the paper simply emphasize something which is overlooked too much in teaching. In electrical engineering, we frequently cannot see the real thing and are forced to adopt conventions in order to make things clear with our limited mental facilities. Now, as long as we have to adopt conventions, we are perfectly at liberty to adopt the one or the other, but the thing that is neglected is to make it perfectly clear that we are dealing with conventions instead of facts. It is all right to teach the separate fluxes to the students, but we must keep in mind that in doing so we are adopting conventions and that the actual resultant fluxes may be different as shown in the paper.

This same point has been discussed for many years, especially in connection with induction motors, where similar problems arise. For instance, if we have induction motor slots (*A*) and (*C*) as shown in Fig. 1, we can represent the main flux by lines (*b*), the primary leakage fluxes by lines (*a*), and the secondary leakage fluxes by (*c*). Now if we assume the extreme case of standstill and zero resistance in the secondary squirrel-cage winding, we know that the resultant flux entering a secondary tooth must be zero; in other words, the secondary leakage flux (*c*) must be equal and opposite to the main flux (*b*). It follows, therefore, that as a matter of fact we do not have separate fluxes (*b* and *c*), but a flux (*d*) which flows around the primary slot, across the air gap, and across the secondary slot opening; in other words, we have here a condition in an induction motor similar to those discussed in the paper for a transformer. Here it is again convenient to adopt conventions dealing with separate main and secondary leakage fluxes, while as a matter of fact, the real fluxes are entirely different. There is no harm in adopting the convention so long as it is made clear that we are dealing with conventions, not actual facts.

Another similar case is the so-called zigzag leakage in induction motors, which is frequently illustrated by a flux line (*a*) as shown in Fig. 2. We have, of course, in addition to the leakage fluxes, the main flux lines (*b*). It is at once evident in this figure that we will not actually have in the air gap portions (P_2) certain fluxes (*a*) flowing in one direction and another flux (*b*) flowing in the opposite direction, but that we actually have a resultant flux density in the gap portions (P_2) which is the difference between the fluxes (*a*) and (*b*). In other words, the zigzag leakage fluxes merely weaken the field in the gap portions (P_2). Similarly, it is evident that the leakage fluxes (*a*) strengthen the flux in the air gap portions (P_1). It is, however, practically impossible for us to work up theories taking into account the effect of the leakage fluxes along the actual line of weakening the main flux in certain portions of the gap and strengthening it in others; while, if we adopt the convention of separate fluxes, the desired result is obtained without much difficulty.

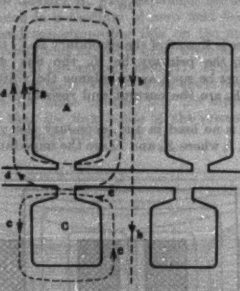

Fig. 1

An exception to the more usual cases, where the leakage fluxes do not actually exist in line with the adopted conventions, is found in the end connection leakage of induction motors. Fig. 3 shows primary core (*D*) and secondary core (*F*), with coil windings in the primary and squirrel-cage windings in the secondary. The main flux is illustrated by a line (*b*). There will be primary end connection fluxes (e_1) going through the air around the coil ends. There will also be secondary end-connection leakages (e_2) going around the end rings of the squirrel-cage motor. These leakage fluxes actually exist separately of the main flux. In addition to these fluxes, there may be other end-connection fluxes (e_3), for instance, which go around the end rings of the secondary, but which go partly through the secondary core. As shown in this latter case, they may not exist separately, but again modify other fluxes.

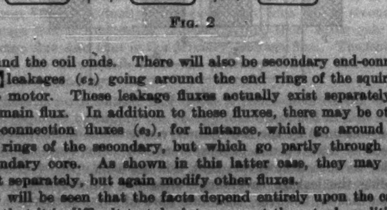

Fig. 2

It will be seen that the facts depend entirely upon the case, and that it is difficult to take into account the actual conditions for all the varieties which are met in practise. The main point is that we must always keep clearly before the student the conventions that are adopted in working out a problem.

P. Trombetta: If the self-inductive reactance of the primary of a transformer is X_0 and of the secondary is X_1 then if the voltage applied to the primary be E_0 the flux Φ_0 surrounding the primary must be such as to balance the voltage $E_0 - R_0 L_0$ where I_0 and R_0 are the current and resistance of the primary circuit.

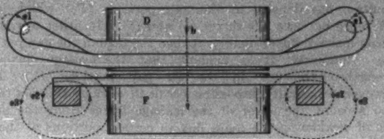

FIG. 3

When there is no load in the secondary the voltage induced in it is $E_0 - Z_0 I_0$ where Z_0 and I_0 are the impedance and current in the primary circuit. When there is a load in the secondary the voltage distribution in it is: $E_1 = E_e + Z_1 I_1$ where E_e is the voltage consumed in the load and $Z_1 I_1$ = voltage consumed in secondary impedance $Z_1 \ I_1 = \gamma_1 i_1 + j x_1 i_1 = i(\gamma_1 + j x_1)$

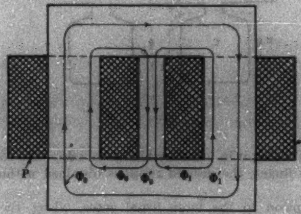

FIG 4

Now it is immaterial whether in the calculations of a transformer or an induction motor we assume that $j x_1 I_1$ is generated and consumed by the self-inductive reactance of the secondary circuit or that it is not generated at all. The most significant point to note is however, that this quantity can be found by finding the leakage reactance voltage of the secondary. The exact fact is, however, that this part of the secondary e. m. f. is not generated at all. In Fig. 4 is shown precisely what actually happens; namely, there are three different sets of lines of forces in the magnetic circuit of the transformer, Φ_0 may be called the main flux and goes through both the primary and secondary, Φ'_0 is the primary leakage flux and goes through the primary coil only, Φ_1' is the secondary leakage flux and goes through the secondary coil only. But it is seen that Φ_1' and Φ_0 are flowing in opposite directions inside of the core while Φ_0' and Φ_0 are flowing in the same direction inside of the core. In the primary, therefore, we have a real leakage flux which actually exists and represents a certain voltage consumption. In the secondary, on the other hand, we have conditions which cannot physically exist. On the outside of the secondary coil Φ_1' and Φ_0 can flow in the same direction and consequently what actually happens is that Φ_1' does not represent a real leakage flux but a part of the main flux which is taken from the inside of the secondary coil to the outside, that is, the flux inside of the secondary coil under load conditions is not Φ_0 but $\Phi_0 - \Phi_1'$ and since Φ_1' represents the leakage voltage, the actual voltage induced in the secondary is:

$$E_1 - j x_1 I_1 = E_e + \gamma_1 I_1$$

In other words, the total voltage induced in the secondary is the voltage consumed in the load plus the resistance drop in the secondary winding. The conditions above described are represented in Fig. 5.

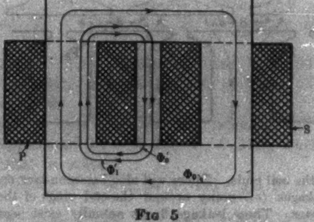

FIG 5

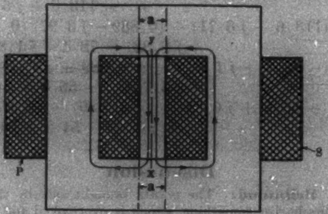

FIG 6

The basis for the above conclusions are to be found in the following physical explanation of reluctance and permeance.

It is well known that every substance (including vacuum which is not a substance but empty space) has a definite coefficient of permeability μ; in some cases this coefficient is variable, in iron for instance. For other substances it is constant. Taking into consideration the fact that we have definite knowledge of μ for those substances for which it is variable, we may state that having given the m. m. f. acting on a magnetic circuit of a certain substance we can calculate the flux flowing through that magnetic circuit. On the other hand if we apply a m.m. f. F_1 to a circuit in which there is already applied a m. m. f. $-F_1$ the resultant flux through that circuit is zero. This may be expressed mathematically in two ways first we may say that the total m. m. f. acting on the circuit is the summation of the two m. m. fs. F_1 and $-F_1$ and therefore equals to zero; second we may say that the permeability of the magnetic circuit has become zero. In either case we are correct. When F_1 is numerically larger or smaller than $-F_1$ there will be some resultant flux and if we write the equation

$$\phi = \frac{F_1}{R}$$

we find that R is very much increased if $F_1 > -F$; while if $F_1 < -F_1$, R actually becomes negative. On the other hand it is found that the permeability of the medium between the two coils has been greatly increased, in other words, in Fig. 6 the permeability of the iron included in the length "*a*" has become of infinite reluctance while the air along the path xy has been made more permeable.

That the application of a m. m. f. to a body is equivalent to increasing its permeability in one direction and decreasing it in the opposite is shown by the fact that electromagnets, whatever may be the nature of the core material, when placed in a magnetic field behave exactly in the same manner as a substance, the permeability of which is such that when exposed to the same field would increase the magnetic flux by the same amount that it would be increased by the new system with substance of different permeability and with a given m.m. f. applied to it.

In other words take (Fig. 7) a solenoid of diameter d and length l with copper core and let a current I flow through it. When this solenoid is placed in a uniform field of intensity H at an angle θ to the axis of the solenoid, it will have a torque T tending to place the solenoid parallel with H. It is now possible to replace the solenoid by a cylinder of diameter d and length l which will give the same torque, provided the permeability is such that the increase in the amount of flux passing through the core for a given amount of rotation of the core is the same as in the case of the solenoid. In other words the torque or couple acting on the cylinder is

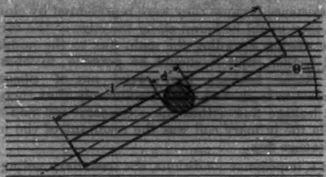

FIG. 7

$$T = K \frac{d\,\phi}{d\,\theta}$$

Where ϕ is the flux passing inside of the cylinder and θ is the angle between the axis of the cylinder and the field intensity of the medium.

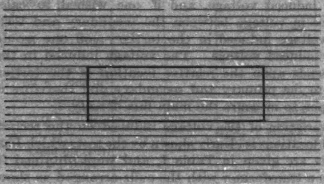

FIG. 8

A further proof of this theory is afforded by the converging or diverging lines into and away from a substance of permeability higher or smaller than that of the ambient in which it is placed, when the ambient has a magnetic field of uniform strength. Thus in Fig. 8 is shown a cylinder of a material of unity permeability placed in air parallel with a field of force of uniform density H, it is seen that the density inside of the rod is the same as that outside, in other words the rod has not converged the field at all.

In Fig. 9 is shown a cylinder of permeability $\mu > 1$ placed in a uniform field of density H. It is seen that inside of the rod the density is higher than it would have been if the rod were not there, while outside the cylinder the density is smaller than it would have been if the cylinder were not there. It is immaterial whether we consider the increase of the flux inside of the cylinder as being constituted by the flux which is now missing outside of it or if we consider all the additional flux inside the cylinder as returning outside of the cylinder in the opposite direction to that of the main field and therefore cancel or neutralize as many lines outside of the cylinder as there have been increased inside of it. In fact it is possible to study the field distribution inside and outside of a cylinder of permeability μ by replacing it by a solenoid through which is flowing a current which will give a field intensity of $H_1 - H$ where H_1 is the density in the permeable cylinder after it has been placed in the uniform field of density H. By exploring the field of this solenoid when placed in a medium of zero field density and unity permeability and superimposing this on the uniform field, we get the exact conditions as would exist when we place a cylinder of permeability μ in the uniform field H. It is evident that if μ of the permeable cylinder were $-\mu$ we could obtain all the field distribution in the same manner but the superposition would have to be so that the flux inside of the solenoid were flowing in opposite direction to the field H.

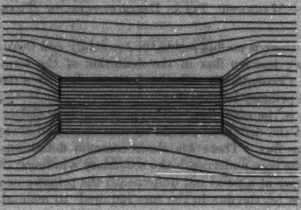

FIG. 9

What Mr. McEachron found by long, tedious and costly work might have been found analytically and much more accurately, and all of it is given in the first edition of Steinmetz's "Theory and Calculations of Electric Circuits," in the chapter on Reactance of Induction Apparatus, p. p. 217-231 (in particular at top of p. 229).

J. E. Clem: In my discussion of this paper I wish first to arrive at a mutual understanding of what the various fluxes are that are found in a transformer.

What is a leakage flux? The definition of the leakage flux should be a statement of the physical phenomenon. A leakage flux is ordinarily defined as a flux which links one winding without linking the other. Two leakage fluxes are sometimes recognized; the first being that produced by the primary current which links the primary but not the secondary and called the primary leakage flux; the second that produced by the secondary current which links the secondary but not the primary and called the secondary leakage flux. Actually, however, the idea of a secondary leakage flux is misleading and erroneous, there being only one leakage flux and that is the primary leakage flux. The leakage flux is the flux which links the primary winding but not the secondary winding.

There is no resultant flux inside a short-circuited coil except that required to supply the energy loss consumed in heat in the short-circuited coil. When the coil is on open circuit the current in the primary coil will cause a certain amount of flux to link the secondary coil, and if the coil is short-circuited a current will be set up and produce a counter flux. The counter flux set up by the current in the short-circuited secondary coil will be at all times exactly equal and opposite to the flux coming from the primary current. Therefore the resultant flux inside the short-circuited secondary coil is zero.

The question immediately arises as to how the current can be maintained in a short-circuited coil with no flux inside it. We have seen that the condition of zero flux is in reality the balance of two fluxes. If the primary current should change there would be an excess of flux in one direction or the other which would induce a voltage and set up an additional current in the secondary coil. The current in the secondary coil will be maintained as long as no change of flux takes place inside the secondary coil.

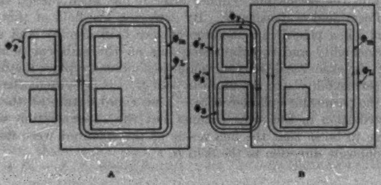

Fig. 10—Magnetic Flux Distribution in Transformers

Since there is no flux inside the secondary coil there can be no secondary leakage flux in the definition of the term as given above. Consequently all the leakage flux in a transformer must be primary leakage flux.

What is the main flux? This is primarily a matter of definition and the definition should be consistent and always lead to the same flux. There are three common definitions; (a) the flux in the core underneath the secondary windings; (b) the flux in the core at a point not underneath the primary or secondary windings; (c) the flux in the core required to maintain the secondary terminal voltage. The first definition is wrong because the flux in the core under the secondary winding is different depending upon whether the primary is inside or outside the secondary. The second is wrong for a reason which will be given later in this discussion. The main flux then is the flux required to maintain the terminal voltage of the secondary winding.

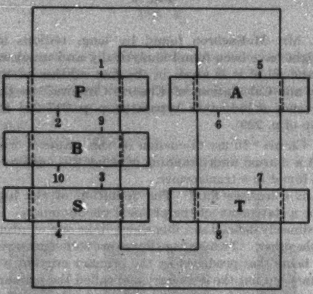

Fig. 11—Magnetic Flux Distribution in Transformers

The leakage and main fluxes as defined above are shown in diagram in Fig. 10A and 10B. In Fig. 10B ϕ_p and ϕ_p' are the fluxes which would exist if the coil *P* was by itself and ϕ_s and ϕ_s' are the fluxes corresponding for coil *S*. Of course in considering the coil alone the core must be assumed as taken away. In Fig. 10A is shown the resultant condition in which the leakage flux is ϕ_p linking the primary winding only. The flux ϕ_L is the flux required to supply the losses in the secondary coil and the flux ϕ_m is the flux required to maintain the terminal voltage of the secondary coil. It is clear that the leakage flux is the flux which links the primary but not the secondary and the main flux is the flux required to maintain the secondary terminal voltage.

The core flux at any part of the core will be the resultant of the various fluxes occurring there. Prof. McEachron's investigation was made to obtain experimental data in respect to the flux existing under the primary and secondary coils and elsewhere in the core. He considered that the text book method of representing the leakage fluxes as indicated in Fig. 1 of his paper required the leakage fluxes to have a separate and independent existence because they were represented by closed lines, and that they would be found along the edge of the core underneath the winding crowding the main flux to the middle of the core and further, that it should be possible to identify the separate fluxes because they were out of phase. Prof. McEachron's tests showed very conclusively that there was no resultant leakage flux within the secondary coil and that the flux within the primary coil was the resultant of the main flux and the leakage flux.

In Test *b*, impedance conditions, the secondary voltage corresponding to the flux inside the secondary coil is 6.14 volts. The voltage consumed in the resistance of the secondary coil is 6.16 volts. All the flux in the secondary coil is that required to supply the energy consumed in the resistance of the secondary coil and there is no other resultant flux inside the secondary coil.

Prof. McEachron's definition of the main flux as "the flux found in the core at a point not under either the primary or secondary windings" naturally led him into a wrong interpretation of the data obtained in test (*b*). According to his definition of the main flux the tertiary voltage should be a measure of the main flux, and he uses this voltage to determine what he calls the primary and secondary reactance. That the results of these calculations should be wrong is the result of the wrong assumption.

The tertiary voltage on the impedance test is a measure of the common reactance of the secondary and tertiary coil or it is a measure of the common induction of the primary and tertiary coils. If one wished to calculate the regulation one would use the difference between the primary applied voltage and the tertiary induced voltage, and if one wished to calculate the difference in voltage between the secondary and tertiary coils or the voltage induced in the tertiary coil one would use the tertiary induced voltage. The voltage induced in the tertiary coil depends upon the relative location of the tertiary coil in respect to the primary and secondary and therefore cannot be relied upon to measure the main flux density.

The variation of the voltage induced on the tertiary coil at different locations is clearly shown by the tests which I have made. The data are given in Table I, and were obtained from tests made on a transformer with the coils arranged as shown in Fig. 11. These tests were made by connecting the generator in turn to coils *P*, *S*, and *T*, with one or both of the other two coils short-circuited and measuring the voltage induced on all the other open-circuited windings. The voltage measured on the open-circuited coils varies with the relative positions of the generator, short-circuited, and open-circuited coils.

The voltage induced in any coil on the core during a straight impedance test can be predetermined if the values of the reactances between the various coils by pairs are known. The method of doing this is illustrated in Table II and the results of the calculation are tabulated in Table I. The voltage induced in a tertiary coil is equal to the secondary voltage plus the resistance drop of the secondary coil plus the common induced voltage of the primary and tertiary. The test and calculated

MAGNETIC FLUX DISTRIBUTION IN TRANSFORMERS

TABLE I

TABULATION OF TEST DATA AND CALCULATED VALUES

Test number	Generator			Induced				
	Volts	Amperes	Watts	Amperes	Amperes	Volts	Volts	Volts
1	1-2 392	60.5	213.0	3-4 59.8		5-6 211 *210.2	7-8 177 *181.4	9-10 196.7 *195.9
2	1-2 1027	60.5	18300		7-8 59.8	5-6 219 *208.7	3-4 835 *780	9-10 926 *880
3	1-2 365	60.5	2400	3-4 50.7	7-8 9.03	5-6 70.5 *97.4		9-10 182.4 *181.8
4	3-4 391.5	60.5	2160	1-2 59.8		5-6 174.5 *181.3	7-8 206 *210.1	9-10 196.7 *196.0
5	3-4 1016	60.5	17350		7-8 59.4	5-6 180.4 *181.9	1-2 845 *778	9-10 928 *873
6	3-4 361	60.5	2200	1-2 49.5	7-8 10.3	5-6 8.22 *63.0		9-10 181.0 *185.4
7	7-8 1036	60.5	18150	1-2 59.8		5-6 825 *783	3-4 197 *210	9-10 104.6 *109.6
8	7-8 1027	60.5	17300		3-4 63.0	5-6 855 *800	1-2 180 *186	9-10 95.5 *97.9
9	7-8 938	60.5	17250	1-2 28.6	3-4 31.1	5-6 746 *700		9-10 8.0 *24.4
10	1-2 403 *401.5	60.3	2360			5-6 223 *220	7-8 187 *191	9-10 204.8 *206.6
	Load on (3-4) 101	60.0	208					
11	1-2 990 *994	60.5	11900			5-6 809 *813.7	7-8 770 *785.6	9-10 791 *785.5
	Load on (3-4) 606	60.0	9290					
12	1-2 1035 *1047	60.5	18200			5-6 228 *220.3	3-4 778 *783	9-10 942 *893
	Load on (7-8) 10.0	59.8	204.0					
13	1-2 1610 *1615	60.0	27400			5-6 805 *876	3-4 1410 *1357	9-10 1503 *1458
	Load on (7-8) 595	59.1	9050					
14	391.7	60.2	2145			Average between 1-2 and 3-4		
15	1037	60.2	18200			Average between 1-2 and 7-8		
16	1006	60.2	17325			Average between 3-4 and 7-8		
17	1021	60.2	17350			Average between 7-8 and 9-10		
18	205.5	60.5	1675			Average between 1-2 and 9-10		

*NOTE—Calculated Values are Marked with *

TABLE 1—*Continued*

Lettering of Coils					Value of Resistance—Based on Wattmeter Readings
1-2	3-4	5-6	7-8	9-10	$R_P = R_S = R_T = 0.3$ when used as secondary
P	*S*	*A*	*T*	*B*	
Value of Reactance at 60 Cycles					$R_P = T_T = 4.72$ when used as primary with other one as secondary
					$R_S = R_T = 4.58$ when used as primary with other one as secondary
P-S *T-A*	*P-T* *S-A*	*S-T* *P-A*	*P-B* *S-B*	*T-B* *A-B*	The difference in resistance whether used as secondary or primary is due to the difference in stray loss which must all be charged up against the primary winding.
6,486	16.46	15.98	3.385	16.26	

MAGNETIC FLUX DISTRIBUTION IN TRANSFORMERS

TABLE II

Calculation of Voltages

Test No. 1

$P.F. = .0898$ $W.F. = .9950$ $I = 53.4 - j\,59.9$

$M_{PT.S} = \frac{1}{2}(6.486 + 15.98 - 16.46) = 3.003$

$M_{PA.S} = \frac{1}{2}(6.486 + 16.46 - 15.98) = 3.483$

$M_{PB.S} = \frac{1}{2}(6.486 + 3.385 - 3.385) = 3.243$

$E_T = (5.34 - j\,59.9)(.3 + j\,3.003) = 181.4$

$E_A = (5.34 - j\,59.9)(.3 + j\,3.483) = 210.2$

$E_B = (5.34 - j\,59.9)(.3 + j\,3.243) = 195.9$

Test No. 2

$P.F. = .2948$ $W.F. = .956$ $I = 17.73 - j\,57.45$

$M_{PS.T} = \frac{1}{2}(16.46 + 15.98 - 6.486) = 12.98$

$M_{PA.T} = \frac{1}{2}(16.46 + 6.486 - 15.98) = 3.483$

$M_{PB.T} = \frac{1}{2}(16.46 + 16.25 - 3.385) = 14.66$

$E_S = (17.73 - j\,57.45)(.3 + j\,12.98) = 780$

$E_A = (17.73 - j\,57.45)(.3 + j\,3.483) = 209.7$

$E_B = (17.75 - j\,57.45)(.3 + j\,14.66) = 880$

Test No. 3

$P.F. = .1093$ $W.F. = .939$ $I_S\ 5.54 - j\,47.58$ $I_T = .99 - j\,9.47$

$M_{SA.P} = \frac{1}{2}(6.486 + 15.98 - 16.46) = 3.003$

$M_{TA.P} = \frac{1}{2}(16.46 + 15.98 - 6.486) = 12.98$

$M_{SB.P} = \frac{1}{2}(6.486 + 3.385 - 3.385) = 3.243$

$M_{TB.P} = \frac{1}{2}(16.46 + 3.385 - 16.25) = 1.798$

$E_A = 365 - (5.54 - j\,47.58)(.3 + j\,3.003) - (.99 - j\,9.47)(4.72 + j\,12.98) = 97.4$

$E_B = 365 - (5.54 - j\,47.58)(.3 + j\,3.243) - (.99 - j\,9.47)(4.72 + j\,1.798) = 181.8$

Test No. 10

$P.F. = .344$ $W.F. = .939$ $I_S = 20.7 - j\,56.5$

$M_{PT.S} = 3.003$

$M_{PA.S} = 3.483$

$M_{PB.S} = 3.243$

$E_T = 10.05 + (20.7 - j\,56.5)(.3 + j\,3.003) = 191$

$E_A = 10.05 + (20.7 - j\,56.5)(.3 + j\,3.483) = 220$

$E_B = 10.05 + (20.7 - j\,56.5)(.3 + j\,3.243) = 206.6$

$E_P = 10.05 + (20.7 - j\,56.5)(.6 + j\,6.486) = 401.5$

Test No. 11

$P.F. = .2544$ $W.F.\ .967$ $I_S = 15.32 - j\,58.25$

$M_{PT.S} = 3.003$ $M_{PA.S} = 3.483$ $M_{PB.S} = 3.243$

$E_T = 606 + (15.32 - j\,58.25)(.3 + j\,3.003) = 785.6$

$E_A = 606 + (15.32 - j\,58.25)(.3 + j\,3.483) = 813.7$

$E_B = 606 + (15.32 - j\,58.25)(.3 + j\,3.243) = 785.5$

$E_P = 606 + (15.32 - j\,58.25)(.6 + j\,6.486) = 994$

values agree very well and bear out the statement that the tertiary coil is not a direct measure of the main flux.

Prof. McEachron could have found the quantities which he calls primary and secondary resistance and reactance much more easily by using an equation based on the analysis I have outlined. It should be remembered however that the quantities are not primary and secondary reactance. If we call the common induction of the primary and tertiary when the secondary is short-circuited M_{pt} then the tertiary voltage will be

$$E_t = I\,(R_s + j\,M_{pt})$$

But $E_t = 24$; $I = 4$; and $R_s = 1.54$, from which M_{pt} is easily found to be 5.8 ohms. Now M_{pt} plus M_{st} must equal X_{rs} and we get M_{st} as 8.85 ohms. The calculations in the paper for the voltage E_m are correctly made although they give the total voltage induced in the tertiary coil and not the voltage induced by the main flux only.

Following is a brief summary of the main points in respect to the magnetic flux distribution in transformers.

There is but one leakage flux and that is the flux which links the primary but not the secondary.

There is no resultant flux inside a short-circuited coil except that required to supply the energy loss in the short-circuited coil.

The main flux is the flux required to maintain the terminal voltage of the secondary winding.

At any point in the core the various fluxes in the core do not have a distinctly separate and independent existence, but the flux at any point is the resultant of the different fluxes at that point.

The voltage induced in the secondary coil is equal to the secondary terminal voltage increased by the resistance drop in the secondary coil.

The voltage induced in the primary coil is equal to the secondary induced voltage increased by the voltage induced by the primary leakage flux.

The voltage induced in any other coil on the core depends upon its relative position in respect to the primary and secondary coils.

The practise of illustrating the various fluxes by closed lines is in general correct because the leakage and main fluxes can exist independently of each other. Whenever two or more fluxes occur at the same point the effective flux is their resultant.

Philip L. Alger: This question of the distinctions between "main flux" and "leakage" is an ever recurring one in the study of electrical machinery. Especially in the consideration of the zigzag leakage or "doubly linked" flux of induction motors are the distinctions difficult to keep in mind. In all cases one has the alternatives of either considering but one flux from which driblets keep leaking away as its path is traced further and further away from the primary source of m. m. f.; or of considering a "main" flux constant throughout the circuit, and various leakage fluxes which flow sometimes with and sometimes against the "main" flux. As an enemy is always defeated more easily in detail than en masse, the latter point of view has advantages for quantitative work, and I prefer it.

While the two points of view, if carried out correctly, will always lead to the same result, the single flux theory is the more fundamental, and should always be resorted to in doubtful cases. Mr. McEachron has presented an interesting experimental proof of this fundamental nature of the single flux viewpoint.

I believe, however, that by modifying his arrangements, Mr. McEachron could have experimentally proved the separate existence of the primary leakage flux (though not that of the secondary). For, if the primary leakage flux actually did try to hug the outer edges of the core as shown by Fig. 1 of the author's paper, the difference in phase between it and the main flux would cause a corresponding difference in the reluctance drops in the iron, and this difference between the m. m. f's. in two adjacent parts of the core would divert the leakage flux in a transverse direction until the m. m. f's were equalized. In other words it is the low reluctance of the core in a direction at right angles to the flow of the main flux (in the section of Fig. 1) that forces the primary leakage and main fluxes to mingle indistinguishably. The question is analogous to that of the distribution of high-frequency current in a slot embedded conductor.

If, therefore, the holes for the research coils had been pierced at right angles to their chosen positions, in the same plane, so that the wires passed *between* instead of *through* the laminations, and if the outer search coils had been so placed as to include only a few of the outermost laminations, a different result would have been found from the experiments. For, in this case the relatively high transverse reluctance of the core, due to the spaces between laminations would have permitted the primary leakage flux to retain its identity more distinctly.

The 15 to 20 per cent excess of density at the middle of the core disclosed by the tests is very interesting. Such differences account for part of the inevitable excess of test core losses over those calculated from the laboratory data. I believe that this variation in density over the core section is due to the fact that the flux always takes a path which combines minimum length with minimum curvature in so far as these qualities are compatible. If the proportions of the test transformers had been different, so that the corners had played a greater (or less) part in determining the flux distribution, I believe the variation of core density would have been correspondingly altered.

P. Trombetta: I still cannot see why it is necessary to make so many assumptions. It seems to me that if the relations are studied properly it is possible to determine all leakage fluxes and when they are known it soon becomes apparent what can and what cannot be neglected. It is perfectly possible to calculate or measure leakage fluxes of primary and secondary at different values of currents and when the two are coexisting in the same magnetic circuit it is only a question of combining all of them and the resultant gives the actual facts.

Benj. F. Bailey: I think the fundamental trouble here perhaps is this. Most of the text books use in a great deal of their work the principle of superposition, yet they never take the trouble to explain that they are using that principle, or what it means. There are a great many effects that can be superimposed upon one another and treated individually. In other words they don't interfere with one another. I look, for example, at the blackboard and I see perfectly what is written there, yet there are innumerable light waves coming across the light waves which reach my eye, but there is not a particle of interference. That is superposition. It is hard to define what we mean by it, but that is simply an illustration of it. There are plenty of places where we can use superposition to advantage. But there are other places where we cannot. One of these is when we come to superimpose magnetic fields. They do not superimpose perfectly because of the change in permeability. Most of the electrical books explain magnetic phenomena on the principle of superposition, but do not make it clear to the student that that is the principle upon which they are working, and also do not make it clear that it may lead to slightly erroneous results. For example in the case of the transformer, they are not taking into account the fact that magnetic effects are not perfectly superimposable. There are changes in permeability, and consequently the result you get is not quite right.

I quite agree with what has been said about the sloppiness of some of our text books. I am a teacher myself, and I have to contend with it every day. It is certainly disconcerting to have to explain to students why the textbook is not right,—and it is not right in a very great many cases.

I think sometimes we might get rid of a good many of the troubles of teaching if we came to the idea of teaching the student that there is no difference at all between a-c. and d-c. current. In other words, Ohm's Law always holds, or the current is the electromotive force divided by the resistance. For example, consider a simple reactive coil. There is an applied voltage on the coil and another voltage induced in the coil. If we take into account both of them and call the sum the electromotive force, then Ohm's law is followed exactly. Now I don't say that I want to teach that way. I am sometimes discouraged, because when I do try to get down to fundamentals and make the thing clear from the ground up, I find it is very difficult to do.

K. B. McEachron: As stated by Mr. Trombetta, a theoretical treatment of the subject of leakage in a transformer may be found in "The Theory and Calculation of Electric Circuits" by Dr. Steinmetz. The present paper attempts only to show in an experimental way the fluxes which are actually found, and to point out how the assumptions frequently made concerning the leakage fluxes may lead the student into an altogether wrong conception of the true conditions.

Mr. Clem in his discussion stated that the method used in determining the main flux does not give a correct measure of this flux. Strictly speaking, that is true, but for this test, it was desirable to obtain a separation of the so-called primary and secondary leakage fluxes. Tests have been made since this paper was written in which I have found, as Mr. Clem stated, several values depending on the location of the tertiary coil. The choice of location of the tertiary coil would not change the final result as outlined in the paper unless placed very close to either the primary or secondary windings.

The possibility of finding the leakage flux in the outer laminations as suggested by Mr. Alger introduces some interesting possibilities. Using the same test core, four belt coils of 40 turns each were wound around equal sections of the core under the middle of coils 7 and 8 shown in Fig. 3 of the paper. To provide sufficient space between laminations for the 80 wires of two adjacent coils it was necessary to separate the laminations 0.03 in. (0.79 mm.). This separation was made only at the point where the coils passed through the core. This arrangement, of course, introduced considerable reluctance in a transverse direction which a core tightly clamped would not have, but does, to some degree, represent the condition in a core where ventilating ducts are used.

The belt coils were numbered 9, 10, 11 and 12, 9 and 12 being on the outside. The procedure followed in making the tests was the same as that described in the paper. Coils 20 and 21 were used as the primary, all tests being made with transformer coils 7 and 8 as the secondary. The first test at no load showed a flux density of 4640 lines in the outer section under belt coil 9, and 4810 in the inner section under coil 10. The oscillograms which were taken all show the same displacement of the belt coil currents with respect to the impressed voltage. This result means that the flux at no load is evenly distributed across the core under the secondary.

With coils 7 and 8 short-circuited and 4 amperes flowing through the windings, a very different result is found. The results are given in the table, the nomenclature being the same as that used in the paper.

Impedance Conditions

Calculated			Belt Coil Tests		
Voltage	B_{max}	Degrees displacement	Belt coil no.	B_{max}	Corrected* angle
E'_p	2790	3.7 lead	9	900	151 lag
E_m	1190	7.5 lag	10	480	6 lag
$I_s X_s$	1100	169.3 lag	11	560	8 lag
E'_s	280	79.2 lag	12	790	152 lag

*The corrected angles are measured on the oscillograms and diminished by the angle found under no load conditions.

Combining the belt coil fluxes, with their respective angles taken into account, gives an average density over the entire core of 260 lines per sq. cm. with a lag angle of 115 deg. In magnitude this corresponds closely to the value of flux required to induce sufficient voltage to overcome the $I R$ drop in the secondary. The phase position does not check very closely.

Considering the position of the belt coil fluxes, it is plain that considerable leakage flux is to be found in the outer laminations, but after all in this particular case such flux is less than 1/3 of the total secondary so-called leakage flux. In the two middle belt coils a flux is found which corresponds to the so-called mutual or main flux in phase position but of less than 1/2 the calculated density. Since the main flux density is calculated on the entire area of the core, something less than 1/4 of the main flux is found.

That some flux due to the secondary and primary turns should be found in the outer laminations is only to be expected when the reluctance of the path perpendicular to the plane of the laminations is taken into account together with the high m.m.f. acting when the transformer is operating under load. In the case of a core with ventilating ducts high flux densities may be found under loaded coils which will tend to change the losses from those calculated assuming a uniform density across the entire core.

Alfred Still: In order to avoid the confusion of ideas which is likely to arise when the various components of the total flux are represented as occupying the same portion of the iron core, the vector diagram for a loaded transformer may be drawn as in Fig. 1.

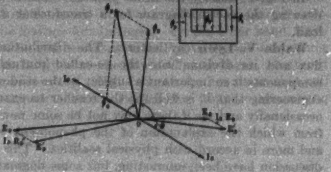

Fig. 1

Owing to magnetic leakage, the flux will not be the same at all sections of the iron core, and it is not possible to represent correctly the flux conditions in the transformer without abandoning the idea of each unit line or tube of induction being closed upon itself. In the sketch of the simple transformer shown in Fig. 1, the lines marked Φ_l represent the leakage flux while Φ_p and Φ_s stand for the fluxes which link with the primary and secondary windings respectively. The arrow-points indicate what will be considered the positive direction of these fluxes. It is then always true that the flux Φ_p is equal to the (vectorial) addition of the fluxes Φ_s and Φ_l, or,

$$\Phi_p = \Phi_s + \Phi_l$$

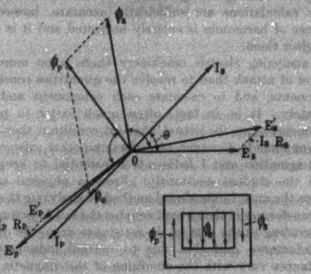

Fig. 2

On the assumption that the magnetizing component of the current is negligible and that the winding ratio is 1 to 1, the vector diagram may be constructed as follows:

Draw $O E_s$ and $O I_s$ to represent the (known) secondary terminal voltage and current with the angle θ between them corresponding to a load power factor of $\cos \theta$. The other vectors are drawn in the following order:

$E_s E_s'$, parallel to $O I_s$ and of the proper length to represent the ohmic drop of $I_s R_s$ volts in the secondary windings.

$O E_s'$, the e. m. f. which must be induced in the secondary windings.

$O \Phi_s$, drawn 90 deg. in advance of E_s', is the flux which links with the secondary windings.

$O\,I_p$, equal and opposite to I_s, is the primary current.

$O\,\Phi_l$, in phase with I_p is the leakage flux.

$O\,\Phi_p$, the resultant obtained by the vectorial addition of Φ_s and Φ_l is the flux which links with the primary windings.

$O\,E_p'$, drawn 90 deg. in advance of Φ_p, is the component of the impressed primary e. m. f. necessary to balance the e. m. f. induced in the primary windings by the flux Φ_p.

$E_p'\,E_p$, parallel to I_p and of the proper length to represent to ohmic drop of $I_p\,R_p$ volts in the primary windings.

$O\,E_p$, the voltage which must be impressed at primary terminals to produce the secondary load conditions which have been assumed.

In Fig. 2, exactly the same procedure has been followed in drawing the vector diagram for a transformer with a capacity load.

Waldo V. Lyon (by letter): The distribution of magnetic flux and its division into the so-called mutual and leakage components is so important a subject to the student of electrical engineering that it is well for the teacher to examine his ideas occasionally and see if there may not be some new point of view from which the explanation of the phenomena will be clearer and more in accord with physical realities. This paper and its discussion have been interesting, but some dogmatic statements have been made which were occasioned, I believe, by a too narrow regard of the problem. Furthermore, some interesting points have not been mentioned. I am sure that all who have discussed the paper will agree that they did not attempt to state new facts, but merely used an unusual method of explaining well known phenomena.

It is well to keep in mind that vector diagrams postulate currents and potentials which vary sinusoidally, a condition that is never exactly reached in a commercial power and lighting transformers. For example, there may be third harmonic component in the full-load primary current of 3 per cent., or in another arrangement, the terminal potential of the primary may contain a third harmonic which is 40 per cent of the fundamental. These harmonics in current and potential are due wholly to the operating characteristics of the transformer. Many calculations are sufficiently accurate, however, if the presence of harmonics is entirely neglected and it is customary to neglect them.

In analyzing electric machinery there is no more powerful method of attack than to resolve the quantities considered into components, and to calculate each component and its effect separately. It is, in fact, often much easier to picture the components than the actual physical condition they represent. The components, however, often have no other existence than in the imagination and I believe it is essential to keep this fact before the student constantly. From a physical standpoint, perhaps the most fundamental method of analyzing the operation of a transformer is that which equates the fall in potential across each winding to the sum of the resistance drop, the drop due to self inductance and that due to mutual inductance. Since inductances vary with the condition of the magnetic circuit, it is necessary to measure or to calculate them for the same condition that exists in the transformer while it is operating. Strictly speaking they are variable, being functions of the actual condition of the magnetic circuit. Although this method is fundamentally correct it is not as convenient to apply as that commonly employed which uses leakage inductances.

In electric machinery, when we can safely neglect all capacitance effects, there are but two sorts of electric potential that we need ordinarily consider, viz: one that is proportional to the current, the $I\,R$ drop, and the other that is proportional to the rate of change of flux linkages, $\frac{d}{d\,t}\,(N\phi)$. The latter is sometimes carelessly written as $N\,\frac{d\,\phi}{d\,t}$, which is, strictly speaking, always incorrect except in those cases in which every tube of a component of flux links every turn. When these flux linkages are due to the current in a transmission line, or in a reactance coil, or when they are due to the so-called leakage flux in a transformer the electromotive force produced by their rate of change is most frequently called a reactance drop. Is it not probable that this term is an extension of the idea of resistance drop in direct-current circuits? In commercial electric circuits the alternating currents are most frequently lagging ones and the effect of these flux linkages is to produce an actual fall in electric pressure just as resistance does in direct-current circuits. The one difference is that in the alternating-current case the subtraction is vectorial. If, however, the alternating current is a leading one the effect of these flux linkages may actually produce a rise in potential, and so it seems that in this case the term drop loses some of its significance. The real physical fact is that a change in flux linkages produces an electromotive force in the circuit, the nature of which does not depend in the slightest upon what is the cause of the flux linkages, whether it be the current in the circuit itself or that in some neighboring circuit. It hardly seems consistent always to refer to the electromotive force that is due to the rate of change of certain flux linkages as a drop in potential and to that which is due to another portion of the flux linkages as a generated electromotive force, meaning a rise in potential. Especially is this so since it is often difficult to distinguish between the two portions of the flux linkages.

The important point that has been brought out in this paper is that the actual generated electromotive force in a transformer is the vector difference between the pressure at the terminals and the resistance drop. The difference is always taken so that the generated electromotive force is greater than the terminal pressure when the winding is delivering electric energy. This of course follows from the assumption that the only sources of potential are due to the rate of change of flux linkages and to the electric resistance of the circuit. For the sake of simplicity consider a transformer that has the same number of primary and secondary turns. When operating under load the magnitudes and relative phases of the primary and secondary terminal pressures and currents can be measured. The net generated electromotive forces in each winding may then be calculated by properly deducting the resistance drops. The vector difference between these generated electromotive forces is due to the difference between the primary and secondary flux linkages and is thus the measure of the leakage in the transformer. The leakage fluxes may actually link either the primary or the secondary or the primary and the secondary, depending upon the arrangement of the windings, the power factor of the load, and the moment in the cycle that is chosen. No statement short of this is general.

Leakage fluxes are those which exist at least partly outside of the magnetic core. The flux that is confined wholly to the core links every turn of both windings. The leakage fluxes on the other hand may link a portion of either or of both windings. The effect of the leakage flux in producing electromotive force depends upon the number of turns with which it links so that the term leakage flux is less useful than leakage flux linkages. If the windings have the same number of turns the total leakage flux linkages are the difference between the primary and secondary flux linkages. Since we are dealing with assumed sinusoidal quantities this difference is taken in a vector sense. The calculation of the primary and secondary leakage flux linkages based on sound physical theory is a difficult problem, and as far as I am aware has never been done.

The actual paths of the flux outside of the magnetic core change from moment to moment during the cycle since they depend upon the relative instantaneous strengths of the primary and secondary currents. It seems to have been assumed by Mr. McEachron and some who discussed the paper that the magnetic flux in the core is always in the same direction in which the primary would produce it, and therefore opposite to the flux which the secondary would of itself produce. This is always true during some portion of the cycle. It is only true during the entire cycle when the power factor of the load on the secondary is approximately equal to the power factor of the transformer at no load. It is true during the major portion of the cycle with highly inductive loads, but with a highly condensive load the magnetization of the core is in the same direction that the secondary would alone produce it during a major portion of the cycle. This is illustrated in the vector diagrams 1, 2 and 3. It must be remembered that it is only by courtesy that the flux in the core and the net exciting current, I_n, can both be represented by vectors. Fig. 1 shows the condition with a highly inductive load on the secondary. Except during a brief portion of the cycle, determined by α, the magnetizing effects of the primary current, I_1, and the net magnetizing current, I_n, are in the same direction and opposed to the secondary current Thus during a major portion of the cycle the distribution of flux may be represented as in Fig. 4. If the load is condensive the primary and secondary currents may be equal as shown in Fig. 2. During a brief interval, determined by β, the currents will magnetize the core in the same direction. During the remainder of the cycle the magnetization of the core will be in the direction in which the primary alone would produce it but one-half of the time. For an equal portion of the cycle the magnetization of the core will be in the direction in which the secondary would produce it. Figs. 5 and 6 show the condition at the moment that the primary and secondary currents are equal and in the same direction. If the windings are symmetrically situated with respect to each other and with respect to the core as indicated in Fig. 5, the flux linkages for the primary and secondary will be the same at the moment when the currents are equal and in the same direction. That is, at this moment there will be no leakage flux linkages. On the other hand, if the windings are arranged as indicated in Fig. 6, the winding nearer the core will probably have the greater flux linkages, whether it be primary or secondary. Fig. 7 shows the condition that will exist at the moment that the mutual flux linkages are passing through the zero. The primary and secondary currents are then essentially equal and opposite in their magnetizing effect. Both the primary and the secondary have actual leakage flux linkage as indicated. Fig. 3 shows the vector diagram for the transformer when supplying a highly condensive load. Except for the portion of the cycle determined by α the magnetization of the core is in the direction in which the secondary alone would produce it. Thus during a major portion of the cycle the flux is distributed as indicated in Fig. 8. There is actual secondary leakage but no pirmary leakage.

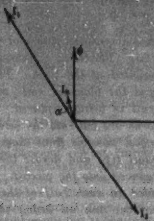

FIG. 1

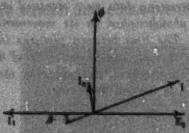

FIG. 2

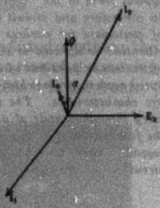

FIG. 3

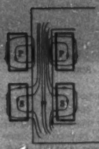

FIG. 4

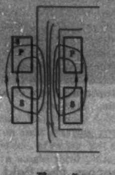

FIG. 5

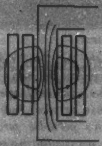
FIG. 6

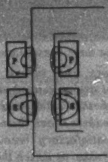

FIG. 7

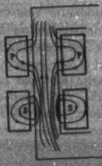

FIG. 8

There is one other point of passing interest. It is that while the flux in the magnetic core is essentially a pulsating one, the flux within the body of the primary and secondary windings is a rotating one. For example, the magnetic fields at the point a in Fig. 5 due to the primary and secondary currents are not in the same direction since the point is not symmetrically located with respect to the windings. The currents are also displaced slightly in time phase. This condition of space and time phase displacement is all that is necessary to produce a rotating field. This field will of course be very decidedly elliptical.

Air-Break Magnetic Blow-Outs

For Contactors and Circuit Breakers Both A-C. and D-C.

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Review of the Subject.—*Magnetic blow-outs have been used in contactors, circuit breakers and controllers for many years for rupturing both a-c. and d-c. power circuits, but their commercial use, particularly on alternating current has been largely confined to relatively low voltages. Oil circuit breakers and switches have been generally used for rupturing high-voltage a-c. power circuits, and their development has reached a high state of perfection. The air break has the advantage of avoiding the possibilities which attend the use of any inflammable material—like oil, with its possible gasification and explosion on heavy short circuits.*

While there are many different types of magnetic blow-outs this paper deals largely with the "individual" type, in which a blow-out coil is connected in series with each pair of current-rupturing contacts, since it is with this type that most of the progress and studies have been made in recent years.

Contactors and circuit breakers with the "individual" type of blow-out are now used almost exclusively in the main d-c. power circuits of the 1500 and 3000-volt d-c. railway systems. Oil circuit breakers have been tried for this service, but they are rather unsatisfactory because there is no periodic zero point in the current wave at which the oil can form an insulating seal between contacts. The oil under d-c. arc conditions carbonizes rapidly and involves the possible danger from explosive gases.

Recently the use of magnetic blow-out contactors on a-c. circuits has been extended to moderately high voltage and capacity. Short-circuit tests on a 6600-volt, 26,700-kv-a. alternator are described towards the end of the paper. During these three-phase tests the air-break magnetic blow-out contactors successfully ruptured 17,500 amperes, the full short-circuit current, at 5500 volts. This is 170,000 kv-a., three-phase. The maximum asymmetrical peak current through the contacts during this test was 67,500 amperes, but during a 2500-volt short-circuit test this peak current reached 80,000 amperes. Oscillograph records of the voltage and current in each phase are shown and also illustrations of the arcs.

The contactors used were rated at 5000 volts, 3000 amperes, but they successfully ruptured a circuit of 9000 volts, 3500 amperes. The oscillographic records and illustrations of this test are shown in Figs. 25 and 26. Current-rupturing tests at 2300 amperes and 3500 amperes normal voltage are also shown for comparison in Figs. 22 to 24. In all of the tests the circuit was ruptured within the first half cycle after the tips started to part, indicating the effectiveness of this type of blow-out.

The arrangement of the current-carrying and magnetic blow-out parts are shown in Fig. 15. The main current is carried through solid copper contacts mounted at the back. The auxiliary contacts in the arc chute and the blow-out coils carry current only during the time the circuit is being ruptured. These coils with their attending arcing horns are cut into the circuit in succession, so as to obtain the strongest possible final magnetic field without undue arcing at the contact tips and across the terminals of the coils when they are introduced into the circuit. Several arc suppressor plates are provided in each half of the arc chute which increases the cooling surface, and on heavy short circuits split the arc into a number of multiple paths. See Fig. 10.

A brief description is given in the first part of the paper of a typical form of the "individual" type magnetic blow-out as used in contactors and circuit breakers, and photographs of a number of contactors for various a-c. and d-c. voltages are reproduced. Attention is directed to the tests with accompanying illustrations of successive positions of the arc in the chute taken with a high-speed camera, from which some interesting data were obtained on arc characteristics. The arc was photographed in its movement every three-thousands of a second. The time between pictures in the familiar motion picture camera is sixty-two-thousandths of a second. These tests bring out the effectiveness, in rupturing the circuit of the arc suppressor plates and narrow arc chutes.

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Typical A-C. and D-C. Contactors. (30 w.)
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Current Rupturing Tests at 600 Volts D-C. (125 w.)
Current Rupturing Tests at 3000 Volts D-C. (80 w.)
Current Rupturing Tests at 6000 Volts D-C. (55 w.)
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THEORY OF THE MAGNETIC BLOW-OUT

IT is a well-known fact that when a conductor of length l carries a current of i amperes in a magnetic field of density of B maxwells per square centimeter, the force F in kg. per centimeter length tending to move the conductor across the field is

$$F = 10.2\, B\, i\, l\, 10^{-8} \text{ kg.}$$

In the same way, when an arc forms between switch contacts which open in a magnetic field, the resulting arc stream will be subjected to the above force and will move across the field and lengthen until the voltage between the contacts is no longer able to maintain a current flow and the circuit is ruptured. It is the function of the magnetic blow-out, which is essentially an electromagnet, to set up the magnetic field over the area within which it is desired to rupture the circuit. To be most effective the direction of the lines of force in the field should be perpendicular to the axis of the arc stream.

The direction of movement of the arc stream is the same as for a conductor moving in a magnetic field, and may be readily determined by Fleming's rules or by the right-hand screw rule. In common with flexible conductors, the arc stream always moves, and in addi-

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tion lengthens, so as to include the maximum number of lines of force. The blow-out coil must, therefore, be wound in such a direction that its flux strengthens the flux encircling the arc stream in the rear of the moving arc stream and consequently weakens it in the front.

FIG. 1—600 VOLT ARMATURE TYPE RAILWAY CONTACTOR

Part of arc chute is removed and placed to one side more clearly to illustrate the magnetic blow-out. When current flows in blow-out coil as indicated by arrow the flux through the core in the blow-out coil is away from reader as indicated by a cross in a circle. This flux returns through arc chute area towards reader as indicated by a dot in a circle. When the contact tips open the arc stream (1) forms and the flux encircling this arc stream strengthens the blow-out flux at the back as indicated by a dot in a circle and a dot in a rectangle and weakens it in front as indicated by a dot in a circle and a cross in a rectangle. As the arc stream always moves from the strong towards the weak field, it will move from position 1 through positions 2 and 3, etc., until the circuit is ruptured.

FIG. 2

Sixteen successive photographs of arc streams taken with a high-speed camera having twenty-four lenses arranged on four slanting rows of six each. In this figure the arc was ruptured 0.06 sec. after the last exposure. The lenses were uncovered in succession by a single focal plane shutter which moved across the plate at such a speed as to expose each point of the arc chute approximately 0.0016 sec. The time between pictures is approximately 0.00328 sec. The successive pictures bring out in particular the changes in the arc stream during a time interval of 0.00328 sec. The delineations on the original films were sufficiently distinct so that the length of arc in each picture could be measured. This length, together with the arc stream current and the time after the contactor tips parted, are indicated for each picture. The inside dimensions of the blow-out coil which can be seen in Figs. 4 and 5 were approximately 10 in. by 21 in. Only the inside area of this blow-out coil was effective in lengthening the arc as the flux is in the wrong direction on the outside of the coil. The maximum length of the arc within the blow-out coil was approximately 35 in.

The circuit was high in inductance. There were five d-c. motor fields in series. Width of chute 1 3/8 in., current about 100 amperes, voltage 650 d-c. This figure is to be compared to Fig. 3 in which the arc chute was 3/8 in. wide.

Fig. 1 shows a typical 600-volt railway contactor having the "individual" type of blow-out, which illustrates the above points. One side of the arc chute is removed to show more clearly the general arrangement of parts. Arrows indicate an assumed direction of current flow through the current-carrying parts and the direction of the resultant lines of force are indicatd by the conventional signs. It will be noted that the direction of the flux in the iron core of the blow-out coil is away from the reader. This flux, after being distributed by the iron pole pieces returns through the arc chute area, strengthening the flux encircling the arc stream at the back and weakening it in front causing the arc to be moved successively through positions 1, 2, 3 until the circuit is ruptured. If the direction of current is reversed through the contactor, the direction of all lines of force will also be reversed, so that the blow-out flux will still strengthen the field back of the arc stream, causing the arc to be moved through positions 1, 2, 3 as before. The arc chute sides which are made of arc-resisting insulation, help to cool the arc and maintain the axis of the arc stream perpendicular to the blow-out flux.

FIG. 3

Sixteen successive photographs of the arc stream taken with a high-speed camera (see details of camera in caption of Fig. 2). Conditions: Same as in Fig. 2 except that the width of arc chute is now 3/8 in. whereas in Fig. 2 it was 1 3/8 in.

FIG. 4

Sixteen successive photographs of the arc stream, taken with a high-speed camera (see details of the camera in the caption of Fig. 2). Conditions: The current now is 500 amperes where it was only 100 amperes in Fig. 2. The arc chute width is 1 3/8 in. This figure is to be compared with Fig. 2 for the effect of variation in current, and with Fig. 5, of the same value of current of 500 amperes, for the effect of the decrease in arc chute width.

ARC CHARACTERISTICS

Some very interesting studies of arc stream characteristics were made some time ago by Mr. F. O. McMillan under the writer's general direction. Figs. 2, 3, 4 and 5 show representative illustrations taken by a high-speed camera invented by Mr. Chester Lichtenberg. This camera has 24 lenses arranged in four slanting rows of six each. The lenses are all served by a single focal plane shutter which first uncovers the lens in the lower right hand corner then the next lens to the left across the bottom row, and so on through the other rows, each row starting at the right. The speed of the shutter was adjusted so that the time interval between each picture was 0.00328 second, and each point of the arc stream was exposed approximately 0.0016 second. In order to photograph the arc, one of the arc chute sides was made of glass, and special blow-out coils were wound giving an approximately uniform flux within the area in which it was desired to rupture the circuit. Oscillographic records were taken of the current and voltage of the circuit, simultaneously with the high-speed photographs. Fig. 6, gives curves plotted from these records, which show the complete arc characteristics when rupturing a 500-ampere, 650-volt inductive circuit in an arc chute ⅜ in wide under the influence of a magnetic blow-out giving a flux density of approximately 2.5 lines per square inch per ampere.

FIG. 5

Ten successive photographs of the arc stream taken with a high-speed camera (see details of the camera in the caption of Fig. 2). Conditions: Same as Fig. 4 except that the arc chute width is now only 3/8 in. where it was 1 3/8 in. in the case of Fig. 4. The current is again 500 amperes. To compare the effects of currents at 500 amperes and 100 amperes refer to Fig. 3, which has the same width of arc chute as Fig. 5.

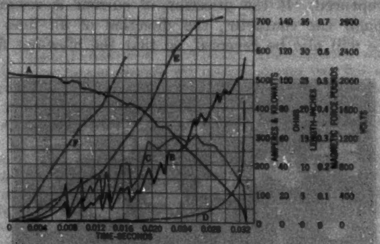

FIG. 6—ARC CHARACTERISTICS

The data for these six curves were obtained from oscillographic records taken in connection with the current-rupturing test recorded in Fig. 5. The width of arc chute was 3/8 in. and the flux density approximately 2.5 lines per square inch per ampere.

Curve *A*—Arc current vs. time in fraction of a sec.
Curve *B*—Arc potential vs. time in fraction of a sec.
Curve *C*—Arc power vs. time in fraction of a sec.
Curve *D*—Arc resistance vs. time in fraction of a sec.
Curve *E*—Arc length vs. time in fraction of a sec.
Curve *F*—Magnetic force on arc vs. time in fraction of a sec.

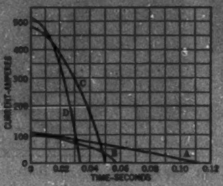

FIG. 7—FOUR CURVES OF TIME VS. CURRENT OF ARCS IN FIGS. 2, 3, 4 AND 5, RESPECTIVELY

Curve *A* corresponds to arc stream in Fig. 2, *B* to Fig. 3 *C* to Fig. 4 and *D* to Fig. 5. The width of arc chute for curves *A* and *C* was 1 3/8 in. and for *B* and *D* 3/8 in. These curves are intended to illustrate the effectiveness of both narrow slots and suppressor plates in the arc chutes. See Fig. 10.

The illustrations in Figs. 2, 3, 4 and 5 bring out in particular the changes in the arc stream during a time interval of 0.00328 second, when rupturing an inductive circuit at currents ranging from 100 to 500 amperes at 650 volts. A summary of the corresponding time characteristics of the arc are plotted in Fig. 7.

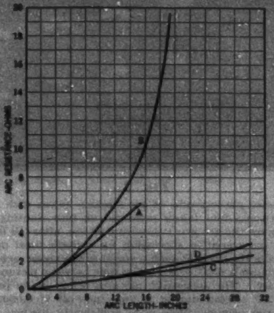

FIG. 8—FOUR CURVES OF LENGTH VS. RESISTANCE OF ARCS IN FIGS. 2, 3, 4 AND 5, RESPECTIVELY

Curve *A* corresponds to arc stream in Fig. 2, *B* to Fig. 3, *C* to Fig. 4 and *D* to Fig. 5. The width of arc chute for curves *A* and *C* was 1 3/8 in. and for *B* and *D* 3/8 in.

THE NARROW ARC CHUTE

Attention is directed to a comparison of Curves *A* and *B* and of *C* and *D* of Fig. 7. The conditions under which the two sets were taken were the same, except the width of the arc chute for curves *A* and *C* was 1⅜ in. and for *B* and *D*, ⅜ in. The narrow arc chute is a recent development and has contributed very materially towards the successful rupturing of high-capacity a-c. and d-c. power circuits.

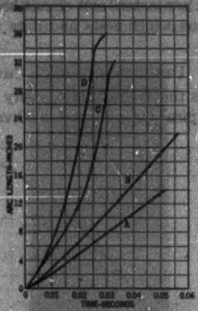

Fig. 9—Four Curves of Time vs. Length of Arcs in Figs. 2, 3, 4 and 5, Respectively

Curve *A* corresponds to arc stream in Fig. 2, *B* to Fig. 3, *C* to Fig. 4 and *D* to Fig. 5. The width of arc chute for curves *A* and *C* wa 1 3/8 in. and for *B* and *D* 3/8 in.

The effect of the narrow arc chute is usually obtained by adding one or more arc suppressor plates to the standard arc chute. This gives a number of multiple paths or slots for the arc. See Fig. 10. Each slot is in the plane of movement of the switch contacts and the exit is materially narrower than the width of the switch contacts and the space within which the arc is formed. These slots reduce the cross section of the arc stream and serve to increase the resistance for a given length. The arc suppressor plates provide additional cooling surface to the arc, and maintain the axis of the arc stream perpendicular to the blow-out flux. In wide arc chutes, the arc stream has a tendency to wander from one side of the chute to the other so that at times its axis is nearly parallel to the blow-out flux.

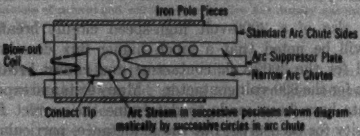
Iron Pole Pieces
Standard Arc Chute Sides
Blow-out Coil
Arc Suppressor Plate
Narrow Arc Chutes
Contact Tip
Arc Stream in successive positions shown diagrammatically by successive circles in arc chute

Fig. 10—Sketch of the Narrow Arc Chute

Arcing horns
Solenoid plunger
Contact tips

Fig. 11—600-Volt, 425-Ampere D-C. Plunger Type Railway Contactor

Part of arc chute removed and placed to one side more clearly to show contact tips and arcing horns.

Fig. 12—3000-Volt, 215 Ampere D-C. Contactor

Two units are used in series for 3000 volts. One arc chute removed to show parts.

It will be noted in both tests where the narrow arc chute was used, the circuit was ruptured in approximately one-half the time of the tests where the wider arc chute was used. This approximate ratio has been found to hold for much higher currents and voltages. The reduction in cross section and quicker opening is plainly evident from a comparison of the time and current printed under each arc stream in Figs. 2 and 3. The narrow chute is particularly effective in connection with high-speed direct-current circuit breakers where it is desirable to rupture the circuit in a few thousandths of a second.

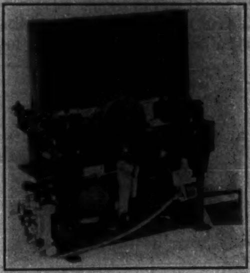

Fig. 13—High-Speed Circuit Breaker

Fig. 8 shows the relation between arc resistance and arc length for both the wide and narrow arc chutes, and Fig. 9 shows the rapidity with which the arc lengthened under the influence of the magnetic blow-out in both widths of the chutes.

In making the above tests on arc chracteristics, it was not possible to rupture very large amounts of power on account of the danger of breaking the glass arc-chute side used for taking the photographs. Current rupturing tests have been made, however, with magnetic blow-out air-break contactors up to 6000 volts d-c. and 9000 volts a-c. and the indications are that still higher voltages can easily be ruptured successfully.

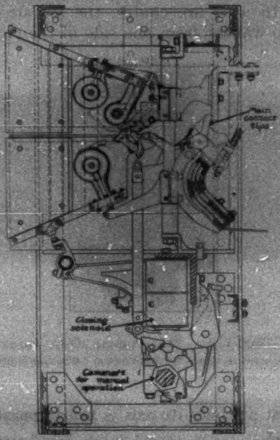

Fig. 14—3500-Volt, 3500-Ampere A-C. Contactor (Closed)

Contactor may be closed either manually, by means of the cam shaft, or electromagnetically by means of the solenoid.

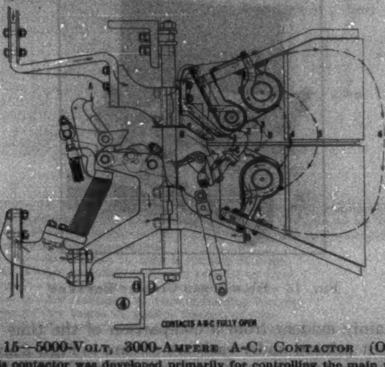

Fig. 15—5000-Volt, 3000-Ampere A-C. Contactor (Open)

This contactor was developed primarily for controlling the main motor circuits of the new 180,000-horse power Battle Cruisers for the U. S. Government. Very exhaustive tests were made before and after the final designs were completed. The results amply met expectations as to the suitability of this type of contactor, not only for ship propulsion, but also for power station service.

Typical A-C. and D-C. Contactors

Figs. 11, 12, 13, 14 and 15 show some typical forms of a-c. and d-c. contactors and circuit breakers for various voltages on which tests and data are presented in this paper.

Flux Density in Arc Chutes

Fig. 16 shows the average flux density curves in the arc chute of typical 600-volt and 3000-volt contactors and also of a 3000-volt high-speed circuit breaker. It will be noted that a much higher flux density is used for the 3000-volt contactors and circuit breaker than for the 600-volt contactor. Many tests and experiments have been made to determine the correct flux density for each type; but the inductance, particularly of railway circuits is so variable that it is difficult to select a flux density to best suit all conditions. In general, a flux density in the arc chute which will cause the current to be reduced at a *rate approximately equal to the initial rate of rise when normal voltage is applied to the circuit,* appears to give about the best average result. See Fig. 17. If the flux density in a particular design is too high, the voltage across the arc increases beyond the breakdown point of the insulation of the arc chute sides and the arc reestablishes a number of times as clearly shown by Fig. 18. Curve *A* of this figure shows the rupture of a 600-volt, 1500-ampere inductive circuit by a magnetic blow-out in which the average flux density in the arc chute at

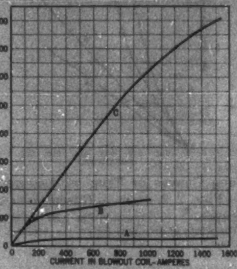

Fig. 16—Arc Chute Flux Density vs. Current in Blow-out Coil

Curve *A*—For 600-volt, 425-ampere contactor.
Curve *B*—For 3000-volt, 215-ampere contactor.
Curve *C*—For 3000-volt high-speed circuit breaker.

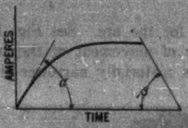

Fig. 17—Theoretical Current-Rupturing Test

Curve showing current decrement to give best average results when opening a circuit. Angle β should be approximately equal to angle α so that the inductive voltage when opening the circuit will not exceed the line voltage.

1500 amperes was approximately 600 lines per sq. in., and Curve *C* approximately the same current and voltage under the influence of a blow-out of approximately 1500 lines per sq. in. Due to the reestablishments it required more than twice the time to rupture the circuit with the blow-out giving the stronger magnetic field. The shape of the arcing horns and the size of the arc chute have a material bearing, however, and by properly proportioning these parts, relatively high densities may be used when it is desirable to rupture the circuit very quickly, as in the high-speed circuit breaker. The principle limitation is then the maximum inductive kick the other apparatus in the circuit will stand.

FIG. 18—OSCILLOGRAPHIC RECORDS OF CURRENT-RUPTURING TESTS

Illustrating the effect of high and low flux densities in the arc chute. Two motor fields were used in series for reactance.

The flux density in the arc chute of the contactor used when rupturing the current shown by Curve *C* was too high for this particular design, being approximately three times that of the contactor when rupturing the current shown by Curve *A*. The current and voltage fluctuations of the arc are very marked on Curves *C* and *D* while there are practically no sudden fluctuations of current and voltage where the low flux density was used as shown by the two upper curves *A* and *B*.

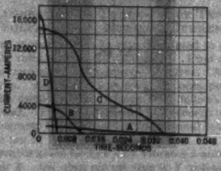

FIG. 19—FOUR CURVES OF TIME VS. CURRENT ILLUSTRATING 600-VOLT D-C. CURRENT-RUPTURING TESTS

Curve *A*—Test with five motor fields in series for reactance using contactor shown in Fig. 11.

Curve *B*—Test with four motor fields in parallel for reactance using contactor shown in Fig. 11.

Curve *C*—Test with no external reactance. Contactor used shown in Fig. 11.

Curve *D*—High-speed circuit breaker. Practically no external reactance.

CURRENT RUPTURING TESTS AT 600 VOLTS D-C.

Curves *A*, *B* and *C* of Fig. 19 plotted from oscillograph records, show typical current-rupturing tests on a 600-volt, 425-ampere d-c. railway contactor. Curve *A* is for a circuit having five motor fields in series for reactance, Curve *B* with four motor fields in parallel and Curve *C* is for a circuit of practically no external inductance. The same contactor was used for all three tests and the strength of blow-out is shown by Curve *A*, Fig. 16. Curve *D* is for a 600-volt, 5000-ampere, d-c. high-speed circuit breaker having a blow-out of approximately the same strength as shown by Curve *C* of Fig. 16. It will be noted that the current of Curve *D*, Fig. 19 was reduced at a very fast rate, averaging approximately 3,500,000 amperes per second.

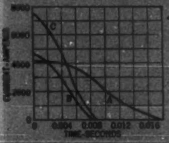

FIG. 20—THREE CURVES OF TIME VS. CURRENT ILLUSTRATING 3000-VOLT D-C. CURRENT-RUPTURING TESTS

Curve *A*—For contactors shown in Fig. 12.

Curves *B* and *C*—For high-speed circuit breaker. See Fig. 13. No external reactance used during tests.

CURRENT RUPTURING TESTS AT 3000 VOLTS D-C.

Fig. 20 shows typical current-rupturing tests at 3000 volts, d-c. Curve *A* is representative of the performance of the contactor shown in Fig. 12 and the strength of the magnetic blow-out is shown by Curve *B* of Fig. 16. Curves *B* and *C* are representative of a 1500-ampere, 3000-volt, high-speed circuit breaker of the type shown in Fig. 13. The average flux density in the arc chute in the neighborhood of the contact tips of a typical high-speed circuit breaker is shown by Curve *C* of Fig. 16.

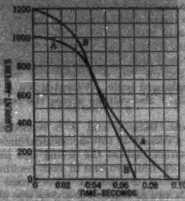

FIG. 21—TWO CURVES OF TIME VS. CURRENT ILLUSTRATING 6000-VOLT D-C. CURRENT-RUPTURING TESTS

Curve *A*—Test with 11 railway motors in series for reactance.

Curve *B*—Test without external reactance.

CURRENT RUPTURING TESTS AT 6000 VOLTS D-C.

Curves *A* and *B* of Fig. 21 are plotted from oscillograph records of current-rupturing tests on a 6000-volt

250-ampere, d-c. contactor. In the test represented by Curve *B* practically no external inductance was used in the circuit while in the tests represented by Curve *A* the fields of 11 railway motors were used in series in the circuit.

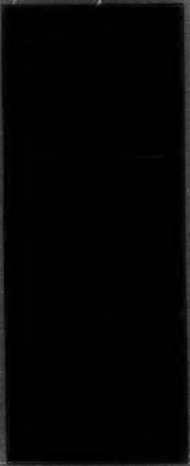

FIG. 22—OSCILLOGRAPHIC RECORDS OF A 5000-VOLT 3500-AMPERE, THREE-PHASE, 25-CYCLE CURRENT-RUPTURING TEST

One contactor as shown in Fig. 15 was connected in each phase. Line voltage initial 5700 volts, under load 5000 volts. First cycle after opening 5280 volts. Line current 3630 amperes effective. External resistance 0.683 ohm per phase. External reactance 0.197 ohm per phase.

Three separate oscillograms operating in synchronism were used for this test, each oscillogram having records of three vibrators. The vibrators in the upper oscillogram are numbered 1, 2 and 3, in the middle oscillogram 4, 5 and 6, and in the lower oscillogram 7, 8 and 9. Vibrator No. 2 shows the current in line 1 and vibrator No. 3 shows the voltage across the terminals of the contactor in this line. Vibrator No. 5 shows the current in line 2 and vibrators No. 6 and No. 9 show the voltage across the terminals of the contactor. Vibrator No. 6 records the same voltage as vibrator No. 9, except on an enlarged scale. Vibrator No. 8 records the current in line 3 and vibrator No. 7 the voltage across the terminals of the contactor in this line.

The voltage between lines 1 and 3 is recorded by vibrator No. 1. Vibrator No. 4 gives a record of the mechanical movement of the contact tips, from which the exact instant the arcing tips parted was determined. This point is recorded on the zero line in each oscillogram by the letter *T*. The circuit was closed by a separate three-phase switch. The current continued for about 4¼ cycles before the arcing tips of the contactor started to part. As soon as the tips parted the voltage across the arc begins to rise. Within one-half cycle after the tips part the line current is reduced to zero and does not reestablish, and the voltage across the contact tips starts to adjust towards normal *Y* voltage. For schematic diagram of connections see Fig. 22*A*.

CURRENT RUPTURING TESTS AT 5000 VOLTS A-C.

Recently the possibility of using magnetic blow-out contactors for rupturing high power a-c. circuits has been recognized and the design and construction has already been completed on contactors rated up to 5000 volts. Fig. 14 shows a typical 3500-volt, 3500-ampere contactor and Fig. 15 a 5000-volt, 3000-ampere contactor, both of which are equipped with a magnetic blow-out of rather novel construction. One side of the arc chute was removed in both contactors to more clearly show the construction. The 3500-volt contactor is shown in the closed position and the 5000-volt one in the open position. It should be noted that the main current is carried through heavy copper contacts, marked *A* in Fig. 15, which are located at the back of the contactor. There are no loops in the path of the main current-carrying parts which might tend to cause overheating on alternating current or to blow the contacts apart on heavy short circuits. The contacts *B* and *C*, located in the arc chute, carry practically no current during normal operation and consequently may be made light and inexpensive.

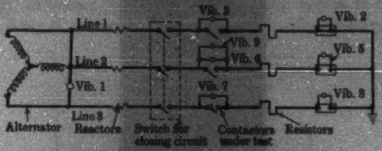

FIG. 22A—SCHEMATIC DIAGRAM OF CONNECTIONS FOR ALTERNATING CURRENT RUPTURING TESTS

Vibrator 1—Voltage between lines 1 and 3.
Vibrator 2—Current in line 1.
Vibrator 3—Voltage across terminals of contactor in line 1 (arc voltage).
Vibrator 4—Records the position and speed of movement of the contacts of the three contactors under test.
Vibrator 5—Current in line 2.
Vibrator 6—Same voltage as vibrator 9 except enlarged deflections.
Vibrator 7—Voltage across terminals of contactor in line 3.
Vibrator 8—Current in line 3.
Vibrator 9—Voltage across terminals of contactor in line 2.
See Figs. 22 to 28, inclusive.

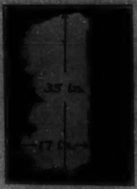

FIG. 23—SHOWING THE LUMINOUS VAPORS OF THE ARC WHEN RUPTURING 5000-VOLTS, 3500-AMPERES, A-C.

The vapors of the three phases blend in one impression on the photographic plate.

When the contactor, Fig. 15 is closed, all three sets of contacts marked *A*, *B* and *C* are in contact. As the contactor opens the tips *A* first part, transferring the main current to contacts *B* located in the arc chute. Further movement towards the open position starts contacts *B* open, transferring the current to contacts *C* and cutting the small blow-out coil at the back of the arc chute into the circuit, as indicated by the arrows. The front tips *C* part next and the arc stream marked

FIG. 24—SHOWING THE LUMINOUS VAPORS OF THE THREE SEPARATE ARCS WHEN RUPTURING 5000-VOLTS, 2300-AMPERES, A-C.

FIG. 25—OSCILLOGRAMS OF A THREE-PHASE TEST AT 25 CYCLES OF OVER-VOLTAGE BUT NORMAL CURRENT RATING

One contactor as shown in Fig. 15 was connected in each phase. Line voltage, initial 9700 volts, under load 7400 volts. First cycle after opening 8700 volts. Line current 3350 amperes effective. External resistance 1.08 ohms per phase. External reactance 0.197 ohm per phase.

The story of the oscillographic records is as follows: There are three separate oscillograms. Each oscillogram has records of three vibrators. Each of the oscillograms has a record of the normal load current and the voltage across the arc of the corresponding phase. In the upper oscillogram the load current is given for line 1 by vibrator 2 and the voltage across the arc by vibrator 3. On open circuit this is Y voltage. In the middle oscillogram the relations are the same for the load current and voltage across the arc of line 2. In the lower oscillogram the current of line 3 is given by vibrator 8 and the corresponding voltage across the arc is given by vibrator 7. In this oscillogram, vibrator 9 repeats the voltage across the arc of line 2 which is given in the oscillogram just above by vibrator 6 with a magnified scale.

Vibrator 1 of the upper oscillogram gives the voltage from line 1 to line 3 and vibrator 4 in the middle oscillogram gives a record of contacts which record the movement of several mechanical parts.

Starting with the record of normal line-to-line voltage at the point marked *A* in the upper oscillogram, the load current in lines 1 and 2 starts at the point marked *B* (shown by a sudden drop in the voltage) and the current in line 3 starts at the point marked *C* which causes a sudden drop again in the voltage and a corresponding change in the load current of line 1 at *D*. Since the neutral of the generator was not grounded, it required the closure of two contacts to start the load current and therefore there are only two disturbances in the main voltage wave. The current in line 1, vibrator 2, continues 2¼ cycles before the arcing tips part. Vibrator 3 shows the beginning of the voltage across the arc at this point. Since the current is extinguished in one-half cycle of arc, as shown by the cessation of wave in vibrator 2 at *E*, the voltage immediately thereafter starts in its adjustment to the normal condition of *Y* voltage from line to ground. This same explanation applies to the other two oscillograms of the other phases.

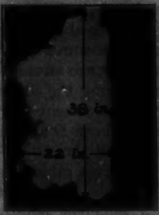

FIG. 26—EXTENT OF THE VAPORS FROM THE ARC BEYOND THE ARC CHUTE WHEN RUPTURING 9000-VOLTS, 3500-AMPERES, A-C.

The photographic plate was exposed during the whole time the gases were being expelled and the vapors from all three phases are superposed.

FIG. 27—5000-VOLT SHORT-CIRCUIT TEST ON 26,700 KV-A. ALTERNATOR

One contactor as shown in Fig. 15 connected in each phase. Initial open circuit voltage 5700 volts. First cycle after opening, 3980 volts. Average line current, at the instant the contactors opened 16,600 amperes effective.

The same arrangement of oscillographs and vibrators was used in this test as described in the caption under Figs. 22 and 22A. This test differs from the normal load test recorded in Fig. 22 in that the external resistance and reactance were removed from the circuit resulting in a dead short circuit on the alternator.

Referring to the record of line voltage in the upper oscillogram, there is a sudden momentary reduction in voltage at the point marked *B* which is due to two of the contacts of the three-phase circuit closing switch making contact ahead of the third, applying a single-phase short circuit through lines 1 and 2 for about 0.008 sec. At the point marked *C* on the line voltage and current waves line 3 was closed establishing the full three-phase short circuit. The short-circuit current was on the contactors for slightly more than three cycles before the arcing tips parted. The instant at which the arcing tips parted is indicated by the letter *T* on all three oscillograms. The circuit was completely ruptured within one-half cycle after the tips parted as evidenced by the cessation of current at the point marked *E*. All the voltage waves are slightly ragged during the time the circuit is being ruptured, that is between points *T* and *E*.

The current in line 1 reached the maximum possible asymmetrical value as the first cycle was displaced entirely on one side of the zero line. The maximum peak value of current in this line was 67,700 amperes. The maximum peak current in line 2 was 48,000 amperes and in line 3, 56,000 amperes. The average effective current in the three lines at the instant the tips parted was about 16,600 amperes.

1 in Fig. 15 forms between the tips. This arc stream is now under the influence of the rear blow-out coil and begins to move rapidly towards the front of the chute. When in position 2, the arc stream touches the lower arcing horn *D* introducing the lower blow-out coil in the circuit. Further movement into position 3 introduces the upper arcing horn *D* and the upper blow-out coil into the circuit. All three blow-out coils are now in series and the arc moves rapidly around the arcing horns *D* through positions 4, 5, and 6 until the arc is stretched out to a sufficient length to rupture the circuit. It will be observed that the arc chute is divided into two parts with the slot between the two halves giving an air gap to more effectively isolate the upper and lower contact tips when the contactor is open. With this arrangement, it is possible to design for a much higher voltage than would otherwise be possible, as most insulations which will stand the high temperature arc streams are usually relatively poor insulators.

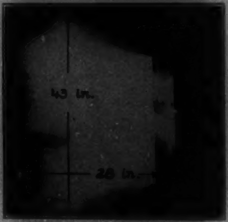

Fig. 28—Showing the Extent of the Luminous Vapors Beyond the Arc Chute when Rupturing Short-Circuit Currents of Fig. 27

As in Figs. 23 and 25, the arcs from the three phases blend in one impression on the photographic plate.

Fig. 22 shows the current and voltage phenomena in all three phases, while rupturing 3500 amperes at 5000 volts, 25 cycles, with the 5000-volt, 3000-ampere, a-c. contactors, shown in Fig. 15. Fig. 23 shows the distance the arc is visible beyond the arc chute. Fig. 24 shows the distance the arc is visible beyond the edge of chutes when rupturing 5000 volts, 2300 amperes under the same conditions. The arcs from all three contactors can be distinguished in the 2300-ampere test, but in the 3500-ampere tests the luminous vapors from the three phases blend in one impression on the photographic plate. The plates were exposed during the whole time the circuits were being ruptured so that the photographs are of value only as showing the maximum distance the luminous vapors were forced beyond the arc chutes by the magnetic blow-out. If the photographs had been taken with a very high-speed multifilm camera the results would have been more like those of Fig. 3.

Fig. 25 shows records of the same contactors, which are rated at 5000 volts, 3000 amperes, rupturing approximately 9000 volts, 3500 amperes, and Fig. 26 shows the extent of the arc. The circuit was ruptured very satisfactorily in this test and there was no evidence that the ultimate rupturing capacity of the contactors had yet been reached.

A dead short circuit on a 26,700-kv-a., 25-cycle alternator, which was very successfully ruptured by the above contactors is shown in Fig. 27. The distance the luminous vapors were forced beyond the arc chute is shown by Fig. 28. Attention is directed to the fact that the maximum asymmetrical peak current carried by the main contacts during this test was approximately 67,500 amperes and that the r. m. s. current (a-c. and d-c. components) at the instant the contactor tips started to part was 17,400 amperes for phase 1, 14,650 amperes for phase 2, and 17,800 amperes for phase 3. The current in each phase was completely ruptured within a ½ cycle after the arcing tips started to part. The fact that the current did not reestablish in the second half cycle after the tips parted indicates the effectiveness of this type of magnetic blow-out.

CONCLUSIONS

While the tests and data presented in this paper are on a-c. and d-c. current-rupturing apparatus of only moderately high-voltage rating, the fundamental principles described for the magnetic blow-outs are applicable to much higher voltages. The tests and experience indicate that we have not yet approached the limit of the alternating voltage or current which may be successfully ruptured repeatedly in the air. In fact we anticipate that within a reasonable period of time the principal of the air-break magnetic blow-out will be extended to cover applications in a-c. power circuits of the higher voltages. There is no question of the ability of the magnetic blow-out to meet the future requirements of high voltage d-c. power circuits.

Discussion

For discussion of this paper see page 282.

The Effect of High Currents on Disconnecting Switches

With Special Reference to the Mechanical Stresses Resulting

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Review of the Subject.—In the early days of the electrical industry, disconnecting switches adequately performed their functions without the use of locking devices, except perhaps in a few isolated cases, where the blades opened downward, and some mechanism was provided to hold the blade in against the action of gravity (when subjected to jars, vibration, etc.). The generating capacity of central stations at this time was relatively small. Hence, the short-circuit currents obtaining were relatively low, and the forces resulting were insufficient to overcome the friction and other resistance offered by the blade and to cause opening. With the increase in generating capacity came a formidable increase in the short-circuit currents, to such an extent that it was not uncommon for a disconnecting switch to open, causing considerable damage, with consequent demoralization of operation. The result was that there were attempts made to attach locks to switches already installed, and to design new switches of which the lock was an integral part. Many of these locks were found to be inadequate, as opening occurred in many instances. In an attempt to prevent the possible recurrence of such unfortunate incidents the tests described in the following paper were planned; it was hoped thereby to improve the class of service rendered the public and safe-guard the lives of our employees.

Specifically, it was desired in addition to a general study of the subject, to attempt to improve the locks already in use on our system and to provide locks for the switches located at dangerous points, i. e., points where short-circuit currents are likely to obtain which might open a given switch. One or more of the various types of switches in use on our system were tested, and in addition, a number of types which were considered for replacement of the obsolescent types now in use.

As a result of these tests it was possible by a very simple expedient to raise the opening point of one of our switches from about 40,000 peak amperes to 180,000 peak amperes. A very simple lock was added to another switch largely used on the system which opened at about 81,000 peak amperes so that it would withstand the mechanical forces exerted by 143,000 peak amperes.

The tests clearly demonstrated that some effective form of lock should be provided. This seems to have been generally recognized, and most manufacturers have attempted to take care of this in some way or other. Switches have been constructed (without locks) in which the current through the switch parts does not tend to open the blade. Such switches are satisfactory when used under almost ideal conditions, but certain unfavorable arrangements of the bus and leads usually found in practise, exert magnetic forces which might open the blade under short-circuit conditions, thus completely nullifying the principle of design. Although locking devices are provided they are not always effective, the various reasons being mechanical weakness of lock, current flow through lock, etc. It was noted from a study of the oscillograms that a switch seldom required more than one cycle to open, one-half cycle usually being required.

It was generally recognized that there were outward forces on the blade of a switch due to the passage of high currents; but it was not generally recognized that there were also outward forces on the jaws and insulators tending to spread them apart. These forces must be recognized and dealt with by substantial design as a number of lock failures may be attributed to this. Insulators may fail due to these outward forces, and this can be remedied only by strengthening or properly supporting the insulators.

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THE forces exerted by the abnormally high currents which obtain under short-circuit conditions on large power systems are often sufficient to cause disconnecting switches to open, rupture current transformers, severely injure oil switches, etc.; and the resulting damage to station apparatus is often very great, and human life is ofttimes endangered; furthermore, short circuits which should cause only voltage disturbance, or at worst, partial loss of load, may result in the total loss of load for an extended period. The following report will cover a number of tests made on disconnecting switches with the object of studying the effects of high currents on this class of apparatus. The principal points observed were:

1. The lowest value of current at which a switch blows open.

2. Time required for the switch to open; that is, duration of the short circuit.

3. Cause of the failure of lock, if such is provided on switch, and remedy for the same.

As a result of the mutual interest in such tests, the Pennsylvania Water and Power Company, and the Consolidated Gas Electric Light and Power Company, both of Baltimore, agreed to perform this work together, thus considerably diminishing the cost of an individual test by either company. Each company furnished at least one of each of its various disconnecting switches, and several manufacturers submitted their switches for test, together with several special switches. Many of the better-known makes of switches were tested, and in addition a number of more or less obsolete types.

METHOD OF TESTS

Difficulty would ordinarily be encountered in obtaining currents up to 100,000 or 150,000 peak amperes necessary for the testing of these disconnecting switches. Fortunately, the Baltimore Electro Alloys Company was able to spare one of its electric furnace transformers, which normally operates at about 40,000 effective secondary amperes. Three of these transformers

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operate in a bank on one furnace, and all three were actually available if necessary; however, one transformer was found to be ample for our tests.

Fig. 1—Bus Structure

These transformers are wound for 13,200 volts on the primary, the voltages on the secondary varying from about 138 to 169 (the secondary voltage is varied by changing taps on the primary). The 158- and 169-volt taps were used on these tests generally. To carry the heavy currents, and to minimize the secondary resistance, standard 8-in. by ⅜-in. cold-rolled copper bus was used. Taps were taken from the secondary of the transformer and run horizontally, as shown in Fig. 1, and then vertically downward. Taps were then taken off of the two vertical busses to the reproduced test bus described below.

In order to simulate existing conditions, a bus structure similar in dimensions to those in actual use in our stations was erected as shown in Fig. 1. The top and bottom phases only of the main and auxiliary bus were erected, as these represent the two extreme conditions. The switches were placed as shown, and tested in this position.

In some of the higher-current tests a loop was used (described later) which required the two bus leads from the transformer being run side by side separated by a ⅜-in. asbestos spacer. These two busses with their spacer were held together by heavy clamps spaced from 12 inches to 17 inches apart along the length of the parallel busses. On one of the tests in which the switch opened in one-half cycle at 141,000 peak amperes, the ⅜-in. by 8-in. copper bus actually buckled out away from the asbestos spacer about ¾ in. in the 17-in. braced section. The calculated maximum force between the axes of the busses in the 17-in. section was about 21,200 lb., applied in .01 second (¼ cycle).

The power for the short circuits was supplied by a generator at our Westport steam station of either 7500 kw. or 20,000 kw. capacity as desired, and was connected to the electric furnace transformer by means of a No. 0000, 13,000-volt, three-phase cable, involving a run of about 30,000 ft.

On some of the tests the power source was the Holtwood generating station about 40 miles away. While one machine was used at Westport, it was necessary to use two 10,000-kw. machines at Holtwood to furnish the higher short-circuit currents; the transformers at each end connected by one transmission line completed the arrangement. The fields of the two machines were arranged to be opened simultaneously.

A third arrangement was used for very low currents on several occasions. A frequency changer running inverted was tied in from one of the city substations, by means of some of the city cables, and this machine was used to supply current.

Telephonic communication was provided between the test floor, the Highlandtown substation and Holtwood (or Westport), and this communication was maintained throughout the test.

In the first few tests the short circuits were made by closing in all switches and then closing the field breaker of the generator, and ammeters were used for measuring the current. It was first thought that this scheme might be used in making the tests, thus obviating the use of the oscillograph, and considerably simplifying the tests. However, it was found that the switches heated very rapidly, and would weld together before the current had risen to a value that would have opened them. The large majority of the tests were suddenly applied by closing the high-tension oil switch (Fig. 2), and the oscillograph was used to record the current through the disconnecting switch under test. A second element of the oscillograph was used to record the potential across the switch, and thereby indicate the exact instant of opening.

Oscillograph Application

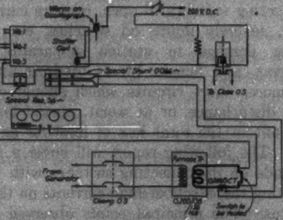

Fig. 2—Oscillograph Set up for Disconnecting Switch Tests

As stated above the oscillograph was used to obtain a record of the current and voltage across the switch under test. The oscillograph used was the General Electric instrument.

In order to measure currents of the magnitude of 100,000 to 150,000 peak amperes a 10,000/5 Westinghouse through type current transformer was used. On some of the later tests a shunt was used which is believed to be more accurate than the current transformer in recording transients. Recent tests have shown that current transformers are subject to error in recording transients, the actual current being greater than that indicated by them.

Fig. 2 shows the scheme of connections for the oscillograph. It was desired to have the apparatus so arranged that the operation of the trigger on the oscillograph performed all the necessary functions after the circuit had been set up for test. The sequence of events should be as follows:

1. Shutter of oscillograph opens exactly at beginning of film.
2. Oil switch closes, applying the short circuit several cycles later.
3. After about one revolution of film, short circuit is cleared.

The third item was not automatic on all of these tests, for it was felt that the repeated clearing of a number of heavy short circuits by an oil switch was undesirable, and so it was decided to clear the short circuit by opening the field of the generator. This was done at the generating station by the operator as soon as he observed that the short circuit was on.

The method of obtaining the required sequence is shown in Fig. 2. Instead of operating the oscillograph shutter from a six-volt battery, 220 volts d-c. was used and an auxiliary relay placed in series with it (the shutter). This relay had its contacts connected to the "close" leads of No. 3 feeder oil switch.[1] When the trigger of the oscillograph was pulled, the moving contact dropped down into the thread of the hard rubber worm and, at the instant the film overlap was opposite the slot, made contact with the metallic thread. This opened the shutter and closed the auxiliary relay which closed the oil switch, throwing on the short circuit. This arrangement caused the initial rush of current to take place near the beginning of the film. The operator at the generating station would then open the field of the machine causing the current to die out.

The oscillograph was at first calibrated before and after each series of tests, but this was found to be unnecessary as there was practically no difference in the two calibrations. Alternating current was used almost exclusively in making the calibrations, principally on account of its convenience..

PROCEDURE IN TEST

After a switch was in place for test the contacts were given a final examination, as was the alignment of the blade and jaws. The pull in pounds necessary to open the switch was then measured at the eye of the switch by means of a spring balance, and this pull adjusted to what was thought to be a normal value, by bending the jaws if necessary. This necessitated further inspection of the jaws for good contact. After the test was made the pull required to open the switch (in case it did not open) was again measured.

When it was desired to make a test on a switch one of the above mentioned circuits was set up with No. 3 feeder oil switch open. When everything was in readiness the operators were notified that the switch would be closed in one-half minute. The oscillograph was given the final adjustments, and at the expiration of the 30 seconds it was operated. The oil switch was opened manually after the film had made one revolution

SUMMARY OF TESTS

	Make	Rating (Amps.)	Fig. No.	Lock	Test Current Peak Amps.	Equivalent Peak Amps.	Did Switch Open?	Pull in lb.	Half-Cycles to open	Remarks
a	A	300	3	No	34,100	34,100	Yes	17	1	
b	"	300	7	Yes	40,500	40,500	Yes	17	1	
c	"	300	8	Yes	84,100	84,100	Yes	16	1	With make *D* lock & ins'l.
d	"	600	..	No	75,000	75,000	Yes	28	2	
d'	"	600	..	Yes	56,700	56,700	Yes	12	1	Note pull is less than *d*
e	"	300	11	Yes	125,000	170,000	Yes	16	13	Notched blade
e'	"	300	..	Yes	133,900	178,000	Yes	20	1	Pinned blade
f	"	300	13	Yes	105,300	127,000	Yes	22	1	Latest type
g	*B*	300	15	Yes	66,800	66,800	Yes	13	1	Type *O*
h	"	300	16	Yes	53,900	53,900	Yes	13	1	Selector type *O*
i	"	300	17	No	39,000	39,000	Yes	20	3	Type *M*
j	"	300	..	No	51,200	51,200	Yes	20	1	Plain Ins'l.
j'	"	300	18	Yes	116,000	148,000	No	20	..	Plain Ins'l.
k	"	600	19	Yes	84,500	84,500	No	35	..	Type *P*. Not completely tested
l	"	300	20	Yes	34,000	34,000	Yes	12	13	Type *P* 35 Kv.
m	"	1200	21	Yes	142,000	208,000	No	40	..	
m'	"	600	..	..	90,700	90,700	..	20	..	Did not open under cond. for which designed
m″	"	1200	22	..	93,000	93,000	No	24	..	
n	*C*	600	..	No	52,200	52,200	Yes	19	5	Lock taken off
n'	"	600	23	Yes	144,000	181,000	No	22	..	
o	"	300	25	Yes	129,000	152,000	No	19	..	
p	*D*	300	..	No	28,200	28,200	Yes	18	1	Selector type
p'	"	300	26	Yes	41,600	41,600	Yes	9	29	
q	"	300	29	Yes	90,900	113,600	Yes	17	6	Insulators broke
r	*E*	300	30	Yes	141,000	169,000	Yes	23	1	
s	*F*	300	31	Yes	74,500	120,000	Yes	27	3	
t	Leilich	600	32	Yes	68,000	68,000	No	12	..	Test not complete
t'	Special	800	33	Yes	81,500	81,500	Yes	90	..	
u	*G*	300	34	Yes	124,100	151,000	Yes	22	9	
v	"	600	..	Yes	145,000	193,000	No	50	..	

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[1] In primary of electric furnace transformers used on these tests.

as by this time the operator had opened the field breaker and the current had died down to a low value. At least one other oil switch was then opened together with the disconnecting switches at the primary of the furnace transformer before anyone was permitted to examine the switch tested. The film was developed and the magnitude of the current ascertained.

FIG. 3

In case the switch did not open another test was usually made at a higher current, but not before carefully dressing and polishing the burned parts.

RESULTS OF TESTS

The accompanying tabulated summary of tests shows both the *test* current and the *equivalent* current. This item "equivalent current" is intended to take care of the added force produced by the rear bus when a switch was tested in the loop (to which reference was previously made). It is the current which would produce the same force met with in test if there should be no rear bus present. If the switch was not tested in the loop, the test current and the equivalent current were the same. The basis of this calculation is the formula proposed by Mr. H. B. Dwight in the June 1920 JOURNAL of the A. I. E. E. As calculated, the effect of the side busses is ignored, and the rear bus only is considered.

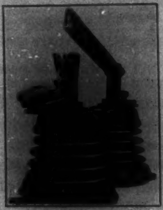


FIG. 4

This tabulation may be used to compare the various switches tested; and in addition a brief discussion of some of the more interesting points of the tests will be given.

It has been previously recognized that there are outward forces on the blade of a disconnecting switch, when subjected to high currents, that tend to open the blade. These forces are shown as $F_1 F_1$, Fig. 3. However, in addition to these forces there are other forces tending to separate the jaws and insulators, as shown at $F_2 F_2$. When the connections are run to the switch as shown by the dotted lines, there is repulsion between these conductors as shown in $F_3 F_3$. In a description of some of the tests in the appendix, it will be shown that many designers of locks have completely ignored the forces $F_2 F_2$ and $F_3 F_3$. These horizontal forces tend to open some types of locks, and to break off the insulators. For this reason locks should be either on the outside of the loop, or some means should be taken to prevent the insulators from spreading.

It was observed on many tests in which the blade opened, that the break jaws spread apart (see Fig. 4). As the two sections of this jaw carry current in the same direction, one would expect them to be drawn together, which occurred only in one or two cases. The only explanation that has been advanced is that the explosive action of the metal vapor or of a small quantity of oil that might be present, forces these sections apart.

In the 43 cases in which the blades of the switches were blown open, 21 cases were within the first half-cycle, 9 cases required one cycle, and 14 cases required more than one cycle for opening. The conclusion might be drawn that a switch will ordinarily open within the first cycle, and possibly within the first half cycle. It is evident from this that it is not the average force exerted by the current which opens the switch, but the maximum force resulting from the peak value of current, and it is this peak-value which should be used in all short-circuit calculations pertaining to the forces acting on disconnecting switches. Furthermore, it is the *initial* peak which will more than likely cause opening. And it should be remembered that this initial peak may have a displacement of twice the symmetrical value usually used in short-circuit calculations.

It was found that the major portion of the locks tested were incorrectly designed. In fact, one manufacturer asserted that electrical expulsion forces only tend to hold this lock more firmly in its place. And as a matter of fact examination of the switch and lock would lead one to believe that such was the case. Yet this particular lock proved to be rather inferior, and blew open at relatively low currents. (Make *F*).

One of the causes of the failure of a number of effective looking locks is due to the fact that designers have failed to take into consideration the fact that in addition to the outward forces on the *blade*, there are outward forces on *each insulator*, which are ofttimes just as effective in causing the lock to open as the outward forces are in causing the blade to open. (Makes *F*, *D*, *B* type *P*).

Another cause of at least two types of locks failing is the fact that the lock itself carries current, and repulsion by other current carrying portions cause the lock to open. (Make *B* Type *C*, *D* Selector type).

Still another cause is due to inherent mechanical ineffectiveness of the lock. By this is meant that the lock simply does not hold even when a simple mechanical pull is exerted on it. In this class would come the two types of Make *D*, and Make *B* type *P* locks.

And there is the switch that has a lock that is not mechanically strong enough to resist the forces. This includes the Make *B* lock on the type *O* selector switch, the Make *A* lock, and the Make *E* lock.

The fact that a lock may carry some of the current may cause it to fail thermally. The failure of the Make *A* lock might be attributed to this cause, as might be the failure of the Make *B* type *O* selector switch lock. As a matter of fact it may have been a combination of mechanical and thermal effect which caused these locks to fail.

Fig. 5

It is desired to call attention to the fact that there is a tendency toward building a switch with the current-carrying portion too light, which is typified in a number of the switches which failed to stand up under test.

Generally speaking, it is believed that the double blade disconnecting switch (such as Make *C*) is superior to the single blade switch, particularly where the design is such that it permits the blades to clamp the jaws due to the parallel high currents flowing in the same direction. Furthermore there is more radiating surface per unit cross section of the blade on this type of switch. It also permits the switch to be so constructed that the contact pressure is readily adjustable.

It may be stated here that while bringing the return circuit behind the switch materially adds to the force action on the blade and hence renders it more liable to open, this is preferable to running it *alongside* of the blade which is still more likely to open the switch. With the return conductor alongside of the blade, a side blow is delivered for which the switch was not designed. This is shown in Fig. 5 where the return conductor was run alongside the blade, and the switch was badly injured.

It is merely repetition to state in this report that switches should not be placed in loops if it is possible to avoid them; but this is usually determined by the original design of the station, and concerns generally station designers rather than operating engineers.

These tests show that the Make *C* switches are generally speaking superior to the other switches tested. This applies to mechanical construction and performance on the tests. Several years ago some difficulty was experienced in these insulators failing on high potential test, but data at hand shows that this defect has been largely remedied.

It might be mentioned here that the split hinge jaw is thought to be undesirable, as it may open instead of the lock. This is described fully in the appendix.

Appendix

This appendix is intended to give briefly detailed information concerning all of the important switches tested. Many switches are included here which may be more or less obsolescent; these switches are included for one of two reasons; first, some point is brought out that is thought to be of general interest; second, these switches are in more or less general use, and the information may be of value to the users.

It is desired to call attention to the fact that these tests were not made primarily to compare the most recent designs of disconnecting switches of the various makes, but to obtain data on switches in actual use on our system.

Over two hundred tests were made, covering in all about thirty types of switches. The manufacturer will in each case be designated by a letter as *A*, *B*, *C*, *D*, *E*, *F* and *G*. It will be noted that peak values of current only are used.

(*a*) *Make A 300-Ampere Switch Without Lock, Fig. 3.* A single blade is provided with a hinge jaw split in three parts, and the break jaw in two parts. The insulators are mounted on the base by means of a clamp and *U*-bolts, and the two jaws are mounted by a similar arrangement. It is believed that this scheme is rather inferior as it permits considerable motion of the insulator.

About 28 tests were made on this switch. The first scheme was to start at a low generator voltage, say 4000, and gradually work upward in steps of 500 or 1000 volts, making three tests at each voltage. But this method was soon found to be unreliable as after a few tests the blade and break jaw would become burned and pitted so that welding would take place, and the switch would not open at all. The method then adopted was to examine the switch to be tested, and estimate the current that it would withstand and test at that current value; then, after an examination of the switch after test, a next higher (or lower) current would be decided upon, and so on until the switch opened. The pull at the eye of the switch was adjusted before each test to be about 15 to 17 pounds, corresponding to 16.5 to 18.5 pounds at the break jaw.

Fig. 6

This switch opened on the first three tests at 43,100, 36,000 and 34,100 peak amperes in ½, 1 and ½ cycles respectively. The latter figure, 34,100, is the lowest value at which the switch opened.

Fig. 6 (Oscillogram 17) shows the switch opening in one-half cycle at 34,100 peak amperes. The mechanical force at the break jaw required to open the switch on tests No. 17 was 18.5 pounds. The current required to exert this force is 38,400 amperes, calculated from the Dwight formula. The switch actually opened at a current 11.2 per cent lower than this (34,100 amperes).

It would be expected that the actual current required would be greater than 38,400 amperes, as the attraction of the two sections of the switch jaws (at the break jaw in particular) should exert a pressure on the blade, thus increasing the pull at the break jaw above 18.5 pounds. The two sections of each of the jaws carry current in the same direction, and hence attract each other.

It was noted that in most cases when the switch blew open the break jaws spread apart. That is best shown in Fig. 4, another type of switch being shown. This may be due to the explosive action of the metal vapor as the switch opens, or to the presence of a small quantity of oil in the jaw, or to both.

Fig. 7

On several subsequent tests the switch failed to open at somewhat higher currents, but this was found to be due to welding. This is shown rather conclusively in tests No. 39 and No. 40, where the burned break jaw of previous tests was replaced by a new one. The switch opened in these two tests at 39,200 peak amperes and 35,900 peak amperes, while on a number of previous tests currents up to 46,500 peak amperes failed to open the switch with the burned jaw in place.

Fig. 8

(b) *Make A 300-Ampere Switch with Make E Lock Attached.*

This switch is identical with the previous switch except that a lock has been added as shown in Fig. 7. The lock is of more or less familiar design, and will not be described further than to say that the latch fits into a notch filed into the jaw of the switch.

Both the hinge and break jaws of the switch are slotted as shown in Fig. 7; and while this probably gives better contact, the switch is materially weakened, especially at the hinge jaw. For when a hole is drilled through the middle section to receive the hinge bolt there is little metal left to resist the outward forces. As a matter of fact, on one of our tests on this switch (described later) the switch blew open at the *hinge* jaw rather than the break jaw due to this weakened condition.

Five tests were made on this switch, which opened at 40,500 peak amperes. From an examination of the lock it would appear that such an arrangement would hold against the action of almost any reasonable current, or at least up to the point where the dogs of the latch would shear off. But it should be remembered that in addition to the outward component of force tending to open the *blade* there is an outward component tending to spread the *break* and *hinge* jaws and pull the latch out of engagement with the notch. This was confirmed by a number of tests in which markings were made on the blade of the switch before test and noting the position after test. Movements of 3/16 in. were frequently noted. Welding of the blade and jaw often took place, and a blow would bring the blade and jaw back into normal contact.

Fig. 9

(c) *Make A 300-Ampere Switch with Make D Lock and Insulators.*

The weakness in the above switch with lock was found to be in the insulators, and it was believed that if more rigid insulators were used the lock would be more effective. Hence the arrangement shown in Fig. 8 was made up similar to the above mentioned switch except that more rigid insulators were used. This arrangement opened at 84,100 peak amperes, or more than double the value with the original insulators (40,500). Fig. 9 (Oscillogram 124) shows the switch opening in one-half cycle. Fig. 10 shows the burning at the break jaw and blade. The jaws in this particular case actually drew together and welded, which is exactly opposite to the action that usually exists, as shown by Fig. 4.

FIG. 10

(d) *Make A 600-Ampere Switch.*

This switch is similar in construction to the 300-ampere switch, with the exception of the current-carrying parts which are correspondingly heavier.

Tests were made with and without lock, as in the 300-ampere switch. Without lock, the opening occurred at 75,000 peak amperes, with a pull at the break jaw of 28 pounds. In testing with lock, the break jaw pull was reduced to 11.5 pounds to make the lock itself withstand the force action, as far as possible. Under these conditions the switch opened at 56,700 peak amperes.

FIG. 11

(e) *Make A 300-Ampere Switch with Special Locks.*

In an effort to find a simple and effective lock for this switch, a number of designs were constructed, such as pin lock (the pin passing through both blade and jaw), door latch arrangement (on the outside of break jaws), notched blade lock, pinned blade lock, etc. Fig. 11 shows a satisfactory arrangement in which the blade of the switch notched so as to fit down over the clamp around the jaws. The object in this arrangement is obviously to prevent the insulators and jaws from spreading with the consequent disengagement of the latch. This scheme was very effective, the current required for opening being 125,000 peak amperes. Opening occurred after 13 cycles, the current having died down to 102,000 peak amperes. The dogs of the latch sheared off as shown in Fig. 11, thus permitting opening. This is one of the few cases in which more than one cycle was required to open a switch. Figure 12 shows the phenomena.

A somewhat similar scheme, designated as the pinned blade lock, held up equally well on subsequent tests. Instead of the blade being notched with a clamp around the break jaws, a pin was driven through the blade which butts against the break jaw thus preventing any outward motion.

FIG. 12

(f) *Make A 300-Ampere Switch with Make A Lock.*

It is understood that at the time of test this switch was the latest design by this manufacturer. The current-carrying portions are very similar to those of the older type; but the insulators show considerable improvement. Fig. 13 shows this switch with the new type of lock in place. Fig. 14 shows a more detailed view of this lock from which its operation is evident. It is believed that the lock occupies considerable space for its effectiveness. Furthermore, the quality of workmanship is not as high as in the other portions of the switch. The insulators are strong and well constructed, and showed no signs of weakness in the tests. The method of mounting the insulators could be improved, as it is necessary to remove the entire switch to make replacements. It is worthy of note

FIG. 13

FIG. 14

that the effectiveness of this lock is not dependent upon the rigidity of the insulators.

The switch was given five tests up to 90,300 peak amperes, which current was effectively withstood. However, burning was evident on all tests, and on the fifth test the blade turned red. A sixth test was made at 105,300 peak amperes, and the switch opened after one-half cycle, burning the blade, jaws, and lock badly as shown in Figs. 13 and 14, these pictures being taken after the last test. It is thought that the tips of the dogs sheared off, permitting the blade to open. The arc then burned the lock, blade and jaws as shown.

The dogs butt directly against one another, and the amount of metal that resists the shear of the blade is small. The lock could be so designed that the two dogs would be staggered and each one would then extend all the way over the blade, thus offering considerably more metal to resist shear.

Test was made with the switch in the loop previously referred to. The calculated force due to this rear bus was 112 pounds at the break jaws, and the force due to the current passing through the switch was 227 pounds, giving a total force of 339 pounds at the break jaw. This force is equivalent to a current of 127,000 peak amperes through the switch, if there were no rear bus present, ignoring the effect of the sides of the loop. The pull at the break jaw was 21.5 pounds for this test.

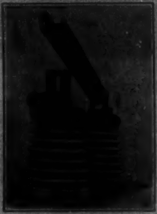


FIG. 15

(*g*) *Make B 300-Ampere Type O Switch with Lock.*

Fig. 15 shows the construction of this rigid insulator switch. The blade is double but is so constructed that it does not properly take advantage of the clamping action of the blades. This clamping action due to the passage of current in the same direction in the two sections, might be utilized in clamping the break jaw, both increasing the friction and insuring better contact. This force action is felt only during the flow of high currents through the blade. The lock is a simple hook arrangement located on the outside of the loop formed by the conducting portion of the switch.

The lowest current at which this switch opened was 66,800 peak amperes in one-half cycle, breaking off the hinge jaw insulator. Burning at the lock indicated that it carried current, and it was thought that forces might have resulted which caused the lock to open. To confirm this suspicion, currents averaging about 60,000 peak amperes, sustained value, were passed through the switch with the blade bolted shut and a contact mechanism in front of the lock (about 3/16 in. distant). This contact mechanism completed a battery circuit through the oscillograph vibrator, and at the above current repeated contact was made as shown on the oscillograph film, indicating that this was the cause of the lock opening.

FIG. 16

(*h*) *Make B 300-Ampere Selector Type O Switch with Lock.*

Fig. 16 shows this switch with its locking mechanism. It is rated at 300 amperes, but the current-carrying parts are fragile as compared to other switches of the same rating. Opening occurred at 53,900 peak amperes. The lock was bent and badly burned. A part of the break jaws welded to the blade, and was pulled off with it when opening occurred (see open blade in Fig. 16).

FIG. 17

FIG. 18

(*i*) *Make B 300-Ampere Type M Switch without Lock.*

The type *M* switch (Fig. 17) is one of the older designs, and was tested for the reason that a number of them are in use at this time. With a break jaw pull of 20 pounds, opening occurred at 39,000 peak amperes.

(j) *Make B 300-Ampere Plain Insulator Switch.*

The name "plain insulator" switch was applied to this type for want of a better name. In fact, there is no marking on the switch to indicate the maker, but the assumption that it was a Make *B* switch was confirmed by one of the maker's representatives. Fig. 18 shows the switch, provided with a lock, described below. While the design of this switch is not beyond criticism, it must be said that the workmanship is as good as on any switch tested, referring principally to the current carrying parts. The current required for opening was 51,200 peak amperes (without lock), with a break jaw pull of 20 pounds.

Fig. 19

As many of these switches were in use on the system located at points where short-circuit currents of sufficient magnitude might obtain to cause opening, it was desired to apply some sort of locking mechanism to this switch that would render it safe up to approximately 100,000 peak amperes. The scheme finally decided upon is shown in the illustration. It has the disadvantage that two motions are required to close and lock the switch, one to close the blade, and one to lock the switch. The first test was made with the lock pedestal insulated, and the blade held satisfactorily at 116,000 peak amperes. The insulation was then removed permitting the lock to carry a portion of the current. It was then tested at 96,600 peak amperes, which was successfully withstood.

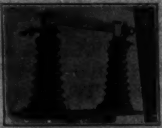


Fig. 20

Testing was with a rear bus present and 116,000 peak amperes is equivalent mechanically to 143,000 peak amperes passing through the switch with no rear bus.

(k) *Make B 600-Ampere Selector Type P Switch with Lock.*

This switch, Fig. 19, was never completely tested, as it was received in such condition as to require considerable dressing before it could be put in service. The type of lock used will be discussed later. It might be mentioned that several tests were made on this switch as received and it did not open (up to 84,500 peak amperes) due to the burning and welding at the contacts.

(l) *Make B 300-Ampere (35,000-Volt) Type P Switch with Lock.*

Fig. 20 shows this switch. The lock is similar to the switch previously mentioned. It is not particularly effective, for it may be opened with a little effort by pulling on the blade. Opening occurred at 34,000 peak amperes, after 6.5 cycles.

Fig. 21

(m) *Make B Switches of other Types.*

Fig. 21 shows a 1200-ampere type *S* switch, one of the later switches of this make. The locking mechanism is fairly simple and substantial. With a pull at the break jaw of 39.5 pounds, 142,000 peak amperes failed to open it. This is equivalent mechanically to 208,000 peak amperes as the test was with a rear bus.

Fig. 22

Fig. 22 shows a 600-ampere switch designed by Mr. F. E. Ricketts, of Baltimore. The principle, that of avoiding loops is obvious. The jaws are so designed that the current passes straight through the switch, thus eliminating any tendency to open. The first group of tests was made with the connections extending in a straight line on either side of the switch for about five feet, thus avoiding loops that would tend to open the blade. With these connections the switch remained closed up to 90,700 peak amperes. The connections were next brought in from the rear at right angles to the blade, in the plane of the blade opening, thus form-

Fig. 23

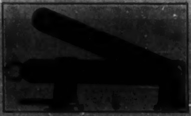


Fig. 24

ing a short loop (about 17.5 in. between the two leads). Opening occurred after 18.5 cycles at 58,300 peak amperes. As the connections to a switch in service are usually as in this last test, it is felt that this scheme is hardly applicable to most installations. The design may prove valuable in bus section switches, or other places where loops are avoided.

Fig. 25

Fig. 26

A 1200-ampere switch of this design was tested up to 93,000 peak amperes, but it showed no signs of distress. No attempt was made to test it further.

Fig. 27

(*n*) *Make C 600-Ampere Switch with Lock.*

Relative to the design and construction of this switch it might be said that it is the equal of any switch tested. Fig. 23 shows the switch to be a double blade switch with jaws and lugs cast integral. The blade is so designed as to take full advantage of the clamping action due to the passage of high currents. The lock is simple and strong. The contact between the blade and jaw is ground giving accurate contact, and these jaws may readily be removed without changing the insulator. Fig. 24 shows the lock mechanism, which is located on the outside of the break jaws. Outward movements of the insulator will not tend to disengage it.

Fig. 28

It was impossible to open this switch at currents up to 144,000 peak amperes, which test was with rear bus, and equivalent mechanically to 181,000 amperes. The burning was relatively slight up to 111,000 peak amperes. Fig. 24 was taken after the tests were completed and shows the relatively slight burning even at these high currents. This switch with its locking mechanism remained operative after the tests were completed.

Fig. 29

Fig. 30

Without locking mechanism this switch opens at 52,200 peak amperes.

(*o*) *Make C 300-Ampere Switch with Lock.*

The 300-ampere switch is similar in design to the 600-ampere switch described previously. Currents up to 129,000 peak amperes failed to open the blade, the mechanical equivalent due to the rear bus being 152,000 peak amperes. On previous tests the blades were drawn together somewhat and the hinge jaw lug was bent due to the burning loose of one of the leads. This lug was straightened out, and on this last test burned loose at the end of the eighth cycle. This is obviously the fault of the bend in the lug, and not an inherent fault in the switch. Fig. 25 shows this burn, and in addition, the drawing together of the blades due to the passage of high currents.

Fig. 31

(*p*) *Make D 300-Ampere Selector Type Switch with Lock.*

This familiar type of switch is shown in Fig. 26, in which the mounting of the insulators with the studs running through to form the back connections, may readily be seen. Attention is called to the large loop formed by these studs which means that a relatively great outward force is exerted on the blade, for a given current through the switch. However, the outward forces on the break and hinge jaws cause no movement due to the method of supporting the insulators. The lock used on this switch consists in a hinged leaf engaging in a notch in front of the break jaw.

The switch was first tested with the lock removed. With a break jaw pull of 16 pounds the opening occurred at 28,200 peak amperes in one-half cycle. The lock was then replaced and the break jaw pull reduced to about 8 pounds. Opening occurred after 15 cycles at 41,600 peak amperes.

The switch was then tested with both of the break jaws alive at one polarity, and the hinge jaw alive at the opposite polarity. The blade opened at 48,100 peak amperes after one cycle and blew into the opposite jaw, thus establishing the current again, blowing back and forth, making four contacts in all. Fig. 27 (oscillogram 74) shows this phenomena with the duration of contact and the interval between.

Fig. 32

Fig. 33

It could not readily be seen just why this lock should open, and the only explanation advanced was that some of the current flowed through the leaf in such a direction as to cause repulsion between the blade and itself. This seemed very unlikely however, and several lock opening tests were made similar to those described above, by bolting the blade to the jaw. The oscillograms showed that the lock opened at the peak of each half cycle. An examination of Fig. 28 (oscillogram 166) shows this opening, the notches in the middle line under the peak of each half wave indicating that the lock opened and made contact.

(q) *Make D 300-Ampere Switch with E N Lock.*

In Fig. 29 is shown one of the latest locks of this make. It will be noted that the hinge jaw is not split which is a very desirable feature. At a current of 90,300 peak amperes the insulators broke off, which evidently permitted the lock to open, but with stronger insulators it is believed that the lock might stand up better. The "equivalent" current in this case was 113,000 peak amperes.

(r) *Make E 300-Ampere Switch with Lock.*

This switch is, generally speaking, more generous in its proportions than many other switches tested. The hinge jaw is not split, making a strong hinge joint. The break jaw is split, but due to the design of the lock, this is not a disadvantage. The locking mechanism is contained in a head riveted on the end of the blade, as shown in Fig. 30.

This switch showed up well up to 75,800 peak amperes but at 141,000 peak amperes (break jaw pull 16 pounds) the blade opened. Examination showed that the head had pulled off of the blade, probably due to the shearing of the three rivets which holds the lock head on the blade. Fig. 4 shows this switch after tests. As this last test was in the loop the 141,000 peak amperes is mechanically equivalent to 169,000 peak amperes.

(s) *Make F 300-Ampere Switch with Lock.*

There are many features in the design of this switch, Fig. 31, which are worthy of note, such as the solid hinge jaw, the adjustable and interchangeable insulators the locking mechanism, etc. To all outward appearances the lock is well made and effective. For this reason no attempt was made to test at the very low currents. Several tests were made in which the blade opened at currents from 65,000 to 75,000 peak amperes.

A thorough examination of the switch was then made to determine just why the lock should open. It was found that when the insulators were spread apart the lock opened, due to the cams on the pull ring pushing against the dogs which open the lock. The remedy that suggested itself was to separate the cams and dogs ⅛ in. by moving the insulators together by this distance. This being done, the switch was tested at 121,700 peak amperes, at which current both insulators broke off and the lock opened, releasing the blade. The current equivalent mechanically to 121,700 peak amperes (due to the rear bus) is 154,000 peak amperes.

(t) *Miscellaneous Makes Tested.*

Fig. 32 shows a cam lock fitted on a standard make switch, designed by Mr. F. T. Leilich of Baltimore. This lock consists of a cam which presses against the break jaw when an outward force is exerted on the blade or jaw. The switch was tested up to 68,000 peak amperes without opening, but injury to the switch prevented it being tested further.

Fig. 34

Fig. 33 shows an arrangement of parts made by various manufacturers and used at various points on the system. With the lock properly adjusted 81,500 peak amperes opened the blade.

(u) *Make G 300-Ampere Switch with Lock.*

In Fig. 34 is shown a switch very similar in design to the Make *C* switch. The photograph was taken after the switch had been opened at 124,100 peak amperes, equivalent mechanically to 152,000 peak amperes. Attention is again called to the drawing together of the blades.

(v) *Make G 600-Ampere Switch with Lock.*

The 600-ampere switch is similar in design to the 300-ampere switch described in the preceding paragraph. Currents up to 145,000 peak amperes, equivalent mechanically to 193,000 peak amperes, failed to open the blade.

Discussion

AIR-BREAK MAGNETIC BLOW-OUTS FOR CONTACTORS AND CIRCUIT BREAKERS, BOTH A-C. AND D-C. (TRITLE) AND THE EFFECT OF HIGH CURRENTS ON DISCONNECTING SWITCHES WITH SPECIAL REFERENCE TO THE MECHANICAL STRESSES RESULTING

(LOUIS AND SINCLAIR).

H. D. James: The investigation of basic arc rupturing phenomena is necessary for the proper design of control apparatus. Mr. Tritle in his paper has made a valuable contribution toward our knowledge of this subject. Similar investigations have been made by Messrs. O. H. Escholz and J. W. Legg. The practical results of these investigations are fundamentally the same but different methods have been followed so that the photographs and curves obtained will supplement Mr. Tritle's paper.

Mr. Legg developed a rotary type of high-speed camera which is fully described in the *Electric Journal* of December 1919. This high-speed camera has been found to be exceedingly useful in the study of arc phenomena, particularly in the development of magnetic blow-out switches. Some of the phenomena disclosed by its use are discussed by Mr. Escholz in the *Electric World*, September 3, 1921, and were reprinted in leading technical papers including the *E. T. Z.* of February, 1922.

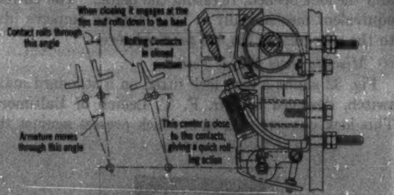

When closing it engages at the tips and rolls down to the heel
Contact rolls through this angle
Rolling Contacts in closed position
Armature moves through this angle
This center is close to the contacts, giving a quick rolling action

FIG. 1—DRAWING SHOWING ACTION OF ROLLING CONTACTS

At the annual meeting of the Association of Iron & Steel Electrical Engineers in September 1919 I presented a paper illustrating a line of magnetic contactors embodying improved arc rupturing means resulting from these investigations. This paper was printed in the *Electric Journal* in November 1919 and also in the *Transaction* of the Iron & Steel Electrical Engineers for that year. I will not repeat the details of these papers as they are a matter of record and can be examined by those interested in this branch of the art.

Briefly described, the electric arc is an elastic conductor consisting of a core of ionized gases surrounded by a luminous gaseous envelope. The arc is ruptured by simultaneously lengthening and cooling it. Every arc has a critical length on constant potential systems and will be ruptured if extended beyond this length. This critical length can be decreased by artificial cooling.

Mr. Tritle has brought out the advantages obtained by cooling the arc and a design of contactor utilizing this cooling effect.

Another form of arc box not only cools the arc but confines the critical length within a smaller area of magnetic field. (See Fig. 1).

This is accomplished by an insulated barrier placed transverse to the arc stream causing the arc to form a double loop so that its length is increased more rapidly than if this barrier or splitter were absent.

In addition to stretching or lengthening the arc, this splitter interposes a cooling surface to the arc stream very shortly after the arc has formed. This is the most effective time to begin cooling because of the high energy density per unit length of the arc stream. The arc splitter may have a piece of copper attached to the tip nearest the arc which very materially assists in increasing the cooling. This copper will not form a part of the arc circuit until the two extreme points of the copper shield have become heated to the point where they will emit electrons and ions. By the time this condition has been reached the arc has been stretched to a very considerable length so that its energy density or heating effect is small and in many cases the copper shield is never heated sufficiently to form a terminal point for the arc.

If the arc box is enlarged, additional barriers or arc splitters may be introduced. These splitters may have copper shields on the tips if conditions warrant. The small contactors operate satisfactorily without the copper tips and even in large contactors or those used on high voltages only a very few arc splitters require copper shields.

FIG. 2—VARIATION IN ARC CONTOUR ON RUPTURING. 40 AMPERES, 250 VOLTS, RESISTANCE LOAD. MAX. LENGTH = 20 IN., 1600 EXPOSURES PER SEC.

When these arc splitters are properly designed and located they are not subjected to any more burning than other parts of the arc box. Referring to Mr. Tritle's illustration, Fig. 10, it is conceivable that transient parallel arcs may be formed in each compartment, but test data have shown that arcs in parallel without individual stabilizing means are exceedingly unstable, and it is to be expected that one of these arcs will be very quickly transferred to the other chamber, thereby reducing the volume efficiency of the arc box.

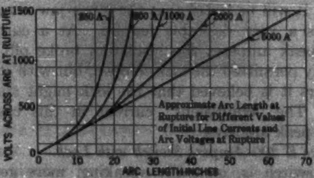
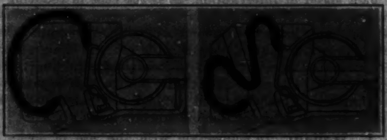


FIG. 3

The dimensions of an arc box are determined by two major factors, the most important being the critical arc length at which rupture occurs and the second the approximate arc width. The critical length of the arc is illustrated by Fig. 3, taken with the high-speed camera. This shows the arc from the time it is first formed until it has reached the critical length where it remains for a short instant and is then ruptured. The critical length of the arcs obtained from test under normal conditions without artificial cooling are shown in Fig. 4 which gives the relation between the volts across the arc at the instant of rupture and the length of arc at that time for various initial line currents. Introducing various cooling agencies will shorten this critical length. Fig. 5 shows the same conditions of ruptures as illustrated in Fig. 3 except with the addition of a barrier transversed to the arc stream. This barrier functions both to cool the arc stream and to cause the formation of a double loop which decreases the area of the arc shield necessary to rupture an arc of a given critical length. An extreme development of the arc splitter is shown in Fig. 6, where three barriers are employed. The illustration at the left shows the arc stream making initial contact with the splitters, and that at the right shows the appearance of the loops immediately prior to rupture. The photograph indicates that the three barriers have not been properly disposed to make the best use of the space. In locating barriers or arc splitters in an arc box, care must be exercised to prevent the retention of incandescent gas and vapor close to the contacts. The effect of such confinement of hot gases can be readily visualized by noting the contour of the incandescent gases in the vicinity of the contacts in this illustration. To minimize the liability of such accumulation of conducting gases it is desirable to provide as free an exit for such gases as possible.

FIG. 4—ARC CONTOUR RUPTURING 400 AMPERES, 250 VOLTS. MAX. LENGTH = 19.5 IN., 1600 EXPOSURES PER SEC. NOTE ARC "SPLITTER"

FIG. 5



Without Arc Splitter With Splitter

FIG. 6—DRAWING OF CONTACTS AND BLOW-OUT UNIT SHOWING RELATIVE PATHS OF ARC

Any restricting means placed in the path of the arc stream will tend to create a back pressure and result in the accumulation of incandescent or conducting gases in the neighborhood of the contacts, therefore, an arc box structure should be proportioned to give ample exit areas. The current density of the arc stream under atmospheric conditions is approximately 500 amperes per sq. in. It is, therefore, evident that if the width of the arc box is less than the normal diameter of the arc stream that this stream will be forced to assume approximately an elliptical shape. This will retard the exit of the arc and its hot gases and augment the accumulation of conducting gases in the vicinity of the contacts.

To summarize, the arc is ruptured by stretching to the critical length.

The rupturing capacity of a given arc box is increased by the use of splitters Figs. 6 and 7, due to:

(a) The cooling effect which decreases the critical arc length.

(b) The confinement of a longer arc stream within the available magnetic field.

The box width and position of barriers should be designed to permit the free exit of conducting gases to avoid arc reignition.

B. G. Jamieson: The problem of interrupting a circuit, under load conditions particularly, is of course a difficult one, and the extent to which this air rupturing may be carried is a thing which will interest all of us. Of course, when we think of the application of this principle to indoor work, the first idea that strikes us is, "How much space can we afford the arc after it leaves these chutes, and how much danger is there of reestablishment of the circuit even after the chute has been cleared?" The pictures given by the author mention the arc in one case as 43 x 28 in. If that is symmetrically disposed across three phases it at once brings to our mind the necessity for doing something with these gases after they have left the chute.

A B

FIG. 7—A. EXAMPLE OF CONTACTOR WITHOUT ARC SPLITTER OPENING CIRCUIT UNDER HEAVY OVERLOAD. B. SAME CONTACTOR EXCEPT EQUIPPED WITH ARC SPLITTER.

In some of the experiences to which the Commonwealth Edison Company have been subjected, the real serious part of the whole affair has been the taking care of the arc after it has left the contacts. A point in that connection which also suggests itself is that there has been a demand created by certain exigencies for circuit breakers, more particularly d-c. perhaps, which will operate within very limited areas or space contents. I was talking with a manufacturer who had been considering the problem of building breakers of the capacity of 1500 amperes, low voltage, and it was necessary to house these breakers, perhaps build them so they could be mounted on 4-in. centers. I asked him if his difficulty lay in the disposal of the arc gases. He told me that much to his surprise the indications were that the disposition of the arc within that enclosed small space was a simple matter, there seemed to be some favorable tendencies of extinguishing the arc, or at least of preventing the re-establishment. So that the point I would like to make is that however efficient this device may be towards the excluding or expulsion of the gases from the point of their origin, to carry this to a successful final usage means perhaps a consideration of the disposal of the gases somewhat beyond the points indicated by the author.

Also there is suggested in this type of circuit rupturing device the question of effect of a passage of those gases past any working parts. I would expect, personally, that there would be considerable damage to parts. Perhaps the design of the breaker takes care of that, but if the breaker is used in a service where it is not convenient to make frequent renewals, it seems to me that more attention perhaps, or more emphasis might have been placed on the adequacy of the breaker with respect to that point.

The paper by Sinclair affords us a somewhat definite measure of the forces and effects operating and produced by certain measured conditions; all operating men have probably experienced some of the untoward results, but they are always at a loss because they don't know, or it is not convenient or easy to determine just what the forces were that produced the results, and that accurate measurement of cause and effect is a very useful step in the determination of the design of apparatus of this sort.

In our own Chicago experience we have had disconnecting switches blow open, not due to the displacement of the blade from the plane of the main conductor alone, but by reason, apparently, of the proximity of other conductors, and there is just a little question whether there isn't a resulting effect which, in the case of three-phase alternating, at least has to be taken into account. Locks have been destroyed when it wasn't possible to account for their destruction by the ordinary explanations given in the paper.

I might add, some years ago, in sort of an experimental attempt, we built some disconnecting switches which were designed to operate directly in the plane of the conductor or rather in the line of the conductor. This switch, if you will imagine a section of a conductor between two insulators removed and a couple of lugs put on the end of those conductors at a distance of 18 inches, and a blade right in the center line of that conductor, you will have an idea of the comparison of the experimental device that we built. We went a little further. We split that blade and we caused it to operate with a scissors-like motion so that the two halves of the blade operating oppositely presented no resultant unbalanced force, so far as the actuation of the device was concerned. Those switches have been in service for some years, and there have been no results, that is to say, no results which would give us any basis for the accuracy of that design. But it would seem as though if we want to get to an easier type of construction, that our difficulty is lessened as we approach the center line of the conductor.

J. B. MacNeill: The theory of the magnetic blow-out is a proper one to apply to switching equipment of any type where it is desirable to cause maximum extension of arc in a minimum time with consequent reduction in amount of arcing and distress on the switching unit. For high currents considerable blow-out effect can be secured by simple relationships of the current carrying parts and without the addition of blow-out coils.

Such a simple and effective relationship is obtained in the ordinary oil circuit breaker where the contacts into and out of the tank form a loop which gives the positive blow-out effect on heavy currents. On light currents, where the blow-out effect is inadequate for rupturing purposes the addition of blow-out coils and magnetic coils gives the desired result. It may be interesting to note that the Westinghouse Co. has been working for some time on the development of oil immersed switching equipment with magnetic blow-outs to secure high speed rupturing of the arc on comparatively low current. This development will probably be published in the near future.

Air switching using magnetic blow-outs will probably find a serious limitation in difficulties of insulation for high voltages. It would appear that even at voltages of 12,000 to 15,000, the insulation difficulties would become very considerable. This difficulty would, of course be greater for outdoor applications than for indoor. Indoor applications of this principle will find some objection from the noise developed when rupturing an arc unless special provisions are made for reducing the same.

The Louis-Sinclair paper brings out very forcibly some features of past disconnecting switch practise which should be avoided in the future and, therefore, paves the way for improvement in this field which is of considerable importance to operating companies as the concentrations of power become heavier.

Given a lock which performs satisfactorily on short-circuit currents, there is still the hazard that an operator may not completely close a switch in which case the lock does not become effective. In this case poor lock and good lock fare alike as the first short circuit that occurs blows the switch open if of sufficient magnitude. The switch shown in Fig. 22 (page 275) of the April Journal was developed to overcome this difficulty. The relationship of the leads to the switch and the blade is such that if the switch is not completely closed the force generated by the short circuit closes it more completely. A disadvantage of this switch is that the leads to and from it must not be looped in such a way as to neutralize the desired magnetic action.

Switch locks have been developed to overcome the difficulty of an operator not latching the switch. The usual method is to have a lock in which the operator cannot remove the hook stick until the switch has been completely latched. Such devices, however, while they have been on the market for several years have not become widely popular, as they can be fooled by the use of a wrong hook stick.

Supposing lock difficulties have been disposed of, there always remains the possibility with an ordinary hook stick type of switch of an operator pulling the wrong switch with serious consequences. In some of the later high powered stations, therefore, remote control, gang operated switches, operated from the breaker aisle and properly inter-locked with the circuit breaker mechanism have been used. Such switches generally are self-locking by a toggle which goes over center in the closed position. Such switches seem to involve minimum risk to operators and maximum ease and speed in operation. The possibility of trouble with such an arrangement is limited to breakage of remote control linkage which is very remote.

F. C. Hanker: The development of the high speed oil circuit breaker is one which will take care of conditions where we want very high speed of interruption, as is the case in reducing the inductive effect of the short-circuit current. The difficulty we will probably have to overcome will be the minimum current we can interrupt; that is, whether the arc will hang on with small current on account of the difficulty of confining the arc to any specific structure such as a chute. On the high voltage type, to get a material that will stand the high arc temperatures and still confine them is one of the difficult problems.

H. L. Wallau: In connection with the use of locks vs. switches the relative hazard might be illustrated by a practise of our own company in which locks are placed on disconnecting switches which are inserted in the main circuits. The disconnecting switches which are used to cut out potential transformers are not so provided. We have never had any trouble with any of these disconnecting switches on potential transformer circuits, and probably one of the reasons for this is that it is our practise to use a No. 14 varnished cambric conductor to make the connections between the bus and the switch and the switch and the transformer. In every case where there has been any transformer trouble this No. 14 conductor has acted as a fuse, the conductor has usually been completely vaporized simply leaving the enclosing envelope of insulation. No damage whatever has been done either to the switch or the cell structure or anything outside of the particular piece of apparatus in which the fault developed.

H. P. Liversidge: The results which have been presented covering the investigation of the performance of disconnecting switches under high-current stresses bring out some very interesting facts, particularly in reference to the resulting mechanical stresses which are imposed upon the entire switch combination. Certainly the tests made under actual current conditions aid very materially in visualizing actual performance, and it is interesting to note that many of the results obtained check very closely with values obtained by calculation. It is unfortunate, however, that in the combination of the various elements making up the completed switch, further consideration was not given to certain factors which, based on the performance recorded in the paper, must be regarded as variables, and because of this, the results—so far as they apply to separate parts of the combination, can hardly be regarded as conclusive.

It is evident from the report that the high-current tests on switches were instituted with the idea of determining the characteristic performance of switch combinations, as used in one particular system. However, as these tests proceeded, it would appear from the report that the performance of switch combinations taken more or less at random, was used as a basis for establishing the characteristics of various specific designs of switches.

In analyzing any switch test of this nature, consideration must be given to a combination of (a) the switch, including the blade and contacts; (b) the switch lock; (c) insulators with their fittings; and (d) the insulator base.

Since the combination of the different parts making up the switch bears a very definite relation to switch performance under conditions of the character imposed by these tests, it is clear that any conclusions which are drawn as the result of such performance must be based upon a correct knowledge of the design and characteristics of the switch in relation to the duty for which it was intended. It is evident that a light-duty combination which was reinforced by a notched blade so arranged as to act as a tie across the tops of the insulator-supports would show better results than another light-duty combination which was not provided with this reinforcement. On the other hand, a combination of switch, insulator and base designed for high mechanical strains, and of comparatively rigid construction, would, if correctly designed, require no bracing to prevent spreading, and the performance would be largely a question of lock design. Under such conditions, therefore, stresses imposed on various combinations of switch and lock would be largely a matter of resisting the outward thrust of the blade alone.

In looking over the report, it is quite evident that the various switches which were tested showed a random selection of locks, insulators and bases, and in combinations, which, under certain tests, gave rather misleading results. As an example, if switches reported as Makes *D* and *F* and shown in Figs. 29 and 31, had been mounted on insulators designed for the duty which was imposed upon them, the results so far as the effectiveness of the lock is concerned would, undoubtedly, have been far different. The conclusions which have been drawn by the authors, therefore, and which refer particularly to the operation of switch locks, cannot be regarded as conclusive insofar as the performance of different types of locks is concerned. In commenting upon locks of Make *F*, the authors state that this particular lock proved to be rather inferior and blew open at relatively low currents. An examination of this switch combination would indicate that this type of lock is designed primarily for use on a rigid type of insulating support and base. Where the amount of energy is very limited, a light-duty type of equipment is furnished; and where the forces are heavier, the insulator design and base are proportionately increased, always with a factor of safety sufficient to prevent any movement of the insulators, and, in this manner, positively prevent any relative movement which would affect the operation of the lock. In the particular test cited, a light-duty combination which was not designed for such expulsion forces, was used. While the lock did not open because of any electrical strains, it was forced open by reason of the spreading of the insulators, and the bending of the flat steel plate insulator base. What was actually tested, therefore, was not the lock but the insulators, and this seems to have been the case in quite a few of the tests recorded. On this particular test, the use of the notched blade furnished under certain requirements, in combination with the light-duty insulator, would quite likely have given the true performance of the lock alone.

The writer trusts, therefore, that the authors will continue the work which they have started and inaugurate a second series of tests with the idea of eliminating the variables included in this first series, so that the performance of locks,—which was evidently one of the principal reasons for instituting the tests—may be investigated under the exact conditions for which the combinations have been designed. Unless such tests are carried to a conclusion, it is felt that quite erroneous impressions covering the relative performance of various makes of locks and switch combinations may be secured.

H. B. Dwight: The method of testing disconnecting switches used by Messrs. Louis and Sinclair is very practical and should be of the greatest value in improving the design of such switches. As in the tests made by Mr. Torchio and described in the JOURNAL of the A. I. E. E. of February, 1921, the disconnecting switches were not subjected to a laboratory test, nor to an imitation of operating conditions, but they were made to carry actual full-size short-circuit currents from large generators. Since the most exacting duty required of disconnecting switches is to carry short-circuit currents, weaknesses or improvements in design disclosed by such tests may be trusted in forming a judgment of the relative value of different designs.

While the final criterion of the value of a design of a disconnecting switch is its performance under actual short-circuit conditions, calculated values of forces are useful in correlating test results, and in pre-determining the operation of the switch when it is not practicable to make full size tests. This is also true of the effect of the neighboring parts of the circuit, one or two cases of which were tested by Messrs. Louis and Sinclair. Many different forms of circuit may arise in practise, and comparisons between them can usually be made by calculation, using the methods, and in many cases the partial formulas, of the complete paper by the writer in the 1920 TRANSACTIONS.

These methods of calculation and partial formulas can be used also for calculating the force at each point of the switch supports, tending to move the insulators apart in a direction parallel to the switch blade, as described by Messrs. Louis and Sinclair.

The comparison between the measured force and the calculated force given in connection with Fig. 6, by which they differ by 11 per cent shows very satisfactory agreement between test and calculation, considering the nature of the test measurement and of the problem calculated. While the currents in the parallel parts of the jaw would tend to squeeze the jaws together and increase the friction, the explosive action of metal vapor or oil vapor in the jaw would tend to decrease the friction, even if it did not force the jaws apart as in Fig. 4. The authors state that "in most cases when the switch blew open the break jaws spread apart." It would be expected that this action would be more pronounced when a lock is used, since heavier currents would flow at the time of opening than would flow if no lock were used.

H. R. Woodrow: The paper by Messrs. Louis and Sinclair bring out two points which I would like to emphasize. One is the effect of the circuit external to the disconnecting switch on the electromagnetic forces on the disconnecting switch. It is therefore, of paramount importance that the operating engineer or the consulting engineer take into account the conductors leading away from or in proximity to the disconnecting switch, in determining the forces on the switches.

The second feature is pulling stresses produced at the clips of the disconnecting switch, which tend to pull the switch in two. This makes it desirable to have the locking device constructed in such a way as to counteract the forces produced in line with the switch, as well as the opening force.

FIG. 8—RECORD OF CHANGE IN ARC DIAMETER, ARC VOLTAGE ARC CURRENT, ON RUPTURING 260 AMPERES, 250 VOLTS. VERTICAL CARBON ELECTRODES.

J. C. Bank: I would like to ask Mr. Tritle what the chances are of developing his switches for out-door use? I am afraid that many of the operators will be somewhat hesitant about putting switches which produce large arcs indoors at the stations, but if they could be put outside, where more space would be available, it would be a very valuable feature.

O. H. Eschholz: Mr. James has referred to two important characteristics of the arc during the period of rupture, *i. e.*, the critical or unstable arc length and the area of cross section of arc stream, that merit further comment.

The critical arc length on rupturing a direct current supplying energy to a resistance load is a function of the line current as well as of the voltage at rupture. For large initial current values it may be computed by assuming one inch length per 22 volts of the line or surge voltage. With the critical length of arc approximated, the contour of the magnetic field may be chosen to assure the application of a positive directional force on the arc stream until rupture occurs.

The selection of arc chute width, location of splitters or barriers and method of breaker ventilation, are determined chiefly by the area of the arc stream section. A narrow arc chute and improper barrier positioning may result in rapid switch depreciation, noisy break and excessive arc duration due to arc reignitions resulting from the trapping of large incandescent gaseous masses near the breaker contacts.

Although the exact determination of the arc stream section is not necessary, some conception of its order of magnitude is essential. Through the use of an ingenious optical system devised by J. W. Legg, simultaneous records of arc voltage, arc current, and approximate arc width, as shown in Fig. 8, were secured. Although the sensitized film is affected by both the wave length and intensity of the radiated energy, it was possible, by the inspection of numerous films, and the known performance of various structures, to arrive at a working value of arc stream diameter. This was found to be roughly in inches, $D = 2\,t + 0.046\ \sqrt{I}$, where t is the thickness of arc envelope in inches and I the initial line current.

The effect of employing too narrow an arc box, or of confining the incandescent gases near the contacts, on arc rupture characteristics is shown in Figs. 9 and 10. For most purposes it was found convenient to determine the arc core section by assuming a current density of 600 amperes per square inch and an envelope thickness varying from ¼ in. to ½ in. depending upon the magnitude of the initial current and the applied voltage.

With the development of similar fundamental data and knowledge of operating principles, it has been found possible to extend the field as well as to place the design of magnetic blowout breakers on a similar plane with that of other electrical apparatus. I am therefore in hearty accord with Mr. Tritle's conclusions that the limiting values of current and voltage that may be successfully ruptured in air have not been reached by service requirements.

J. F. Tritle: I wish to thank Mr. James for his very excellent contributions to the subject, having in mind particularly Mr. Jamieson's remarks on the desirability of rupturing these arcs in the smallest possible space. It seems to me that any device or combination of devices which helps in doing this materially advances the art.

The arc barrier placed transverse to the arc stream, described by Mr. James, certainly cuts down the amount of vapor, and increases the rupturing capacity of a given design. We also made tests on arc barriers of this kind and our results more or less checked Mr. James' results. However, when rupturing high power circuits at 600, 1500, 3000 and 6000 volts we obtained materially better results from the arc suppressor plates; which split the arc into a plurality of multiple connected paths.

Of course, the number of arc suppressor plates and the width of the slots must be properly proportioned for each particular design so as to provide for the exit of the maximum arc with the attending hot gases. We consider it an advantage to have the width of the arc box or the slots less than the normal diameter of the arc stream, as this arrangement forces the arc stream to take an elliptical shape, thus giving the maximum area in contact with the arc chute sides for cooling effect.

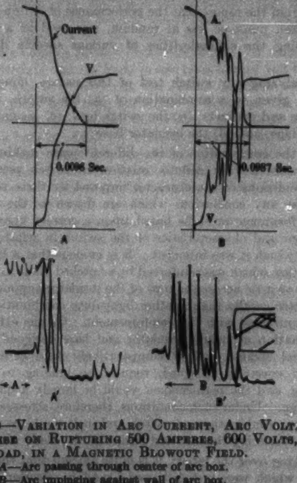


FIG. 9—VARIATION IN ARC CURRENT, ARC VOLTAGE AND ARC NOISE ON RUPTURING 500 AMPERES, 600 VOLTS, RESISTANCE LOAD, IN A MAGNETIC BLOWOUT FIELD.

A and *A*—Arc passing through center of arc box.

B and *B*—Arc impinging against wall of arc box.

The switch noise intensity was approximately recorded by securing the oscillographic record of resistance variation in a granular-carbon type of telephone transmitter, upon the impact of sound waves. It will be noted that the current and voltage changes in *A* are quite regular, while in *B* both oscillate at moderately high frequencies. These oscillations produced a ripping or tearing noise in *B* having a higher intensity and pitch than the more muffled sound in *A*.

Our tests indicate, that as the normal cross section of the arc stream is reduced the arc resistance is increased and therefore the critical arc length is reduced. When the arc suppressor plates and narrow slots are used, we can assume in excess of 40 volts per inch length of arc rather than the figure of 22 volts mentioned by Mr. Escholz.

Regarding the instability of the transient parallel arcs illustrated in Fig. 10 of the paper, it is true that these arcs are very unstable, but photographs taken looking into all the slots distinctly show the hot vapors coming out of all of them, particularly when rupturing heavy currents. We have not been able to measure the exact distribution of current, and it is probable that the final rupture of the circuit takes place in one slot. The other slots and suppressor plates, however, are effective in absorbing energy from the circuit when the arc stream current is the highest.

Mr. Jamieson commented on the space required for rupturing the circuit with this air break device. I agree that the amount of space, 43 by 28 inches, appears rather large. However, this particular contactor was really designed for a lower voltage. That is, when we started out we had in mind rupturing only about 2500 volts, and something like 1500 to 2000 amperes. As the tests developed, we found we were able to rupture a great deal more power than that. If the arc chute had been designed especially for the higher voltage and current, the amount of vapor outside of the arc chute could have been very materially decreased. Fig. 24 is more nearly illustrative of normal conditions. In this test 5000 volts and 2300 amperes were ruptured, and the luminous vapors came out only four inches. In addition, it is possible to put covers over the front of the arc chute so as to direct the vapors. For instance, on a three-phase circuit you can direct the vapors from one phase up, the second phase out and the third phase down so as to practically eliminate the danger of short circuits between phases. Regarding the effect of the passage of the gases through the arc chute. It is quite possible to design both the arcing horns and the arc chutes side to have a very long life. The arc is moved through the arc chute so quickly that it doesn't have time to rapidly erode or burn away any one particular spot. One of the outstanding advantages of the air break contactor is the large number of short circuits or heavy currents which may be successively ruptured without attention to the arc chutes and current carrying parts.

Fig. 10—Arc Re-Ignitions

Arc rupture characteristics of an experimental switch under conditions causing pocketing of incandescent, conducting gases in region of contacts. Note arc stream development and the two subsequent arc re-ignitions at the contacts shown both in the oscillographic and photographic records.

Mr. Trombetta asked about the progress of development work to decrease the amount of gases. The arc suppressor plates, arc barriers and the arrangement described by Mr. Creighton are the most effective means that I know of.

Regarding the effect of inductance and speed of rupture on the length of the arc, inductance increases the arc voltage, so that necessarily in rupturing an inductive circuit a much longer arc results than from a non inductive circuit. I don't know that there is any particular relation between speed of rupture and arc length.

Mr. Bank inquired about the chances for outdoor installations. The type of contactor described has all the parts exposed, and for outdoor service it would be necessary to provide a switch house or enclosure to protect it against the weather.

The design shown in Fig. 14, is arranged for both cam operation and for remote control by means of a solenoid so that it would be suitable for this kind of an installation or for mounting on galleries in the main station at a distance from the operator.

C. T. Sinclair: We realize the short-comings and incompleteness of our tests, particularly with regard to the effect of return conductors on adjacent switches carrying short-circuit currents. For example, our tests in only one or two instances were concerned with the effect of an adjacent conductor, as explained in the description relative to Fig. 5. But where we have three disconnecting switches located in compartments relatively close together, it is evident that a short circuit between phases will produce forces, as Mr. Woodrow and Mr. Jamieson brought out, on the other switches which will mutually react on one another. The nature of the short circuit will determine the phase displacement of the several currents involved and consequently any calculation would have to take this displacement into consideration.

I was very much interested in the switch described by Mr. Jamieson which is apparently very similar in principle to Mr. Rickett's switch; that is, a switch in which the current passes straight through the conducting elements. In Fig. 32 in the paper is shown a cam lock switch which was designed by F. T. Leilich of Baltimore. This switch was constructed partially to take care of the difficulty as outlined by Mr. MacNeill, that the operator might not close the switch far enough to cause it to lock; in case this switch is even partially closed the cam lock will hold effectively. The tests on this switch are unfortunately, not complete.

Regarding the criticism of Mr. Liversidge, I would like to say this: that the authors attempted to bring out these very points in this paper, that the *combination* of lock, switch and insulators is of paramount importance. This is simply another illustration of the fact that a chain is no stronger than its weakest link, and apparently in the switch referred to by Mr. Liversidge, the weakest link is in the insulator and mounting. I assume the reference is to Fig. 31, which is a switch that was submitted to us for test by a manufacturer. We requested that the manufacturer send us a switch with *heavy duty insulators*. Not being familiar with this particular manufacturer's design, we could only assume that we had received the switch with insulators as requested by us and as specified by them.

H. C. Louis: I would like to accentuate the fact that it is not our intention in this paper to criticise for the sake of condemnation any particular designs or makes of disconnecting switches but to impress on manufacturers and operating companies the importance of understanding and taking care of the various factors involved. Mr. Liversidge in his discussion has stated that the performance under our tests of a certain lock was not due to the design of the lock itself but to other circumstances. This is another example of the necessity of considering all factors involved, which as an operating man, I can appreciate very much.

A piece of apparatus is installed, designed and expected to do certain things; it fails to do so, perhaps due to secondary effects, not previously realized; the operating company suffers severe inconveniences and losses, and the manufacturer may be compelled to change it. So, therefore, it seems that if such facts as are brought out in this paper are not taken as merely adverse criticism but as an intended help, for all concerned, both manfacturer and user will be benefited.

The Physical Nature of the Electrical Breakdown of Solid Dielectrics

BY KARL WILLY WAGNER

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WHILE the physical phenomena in connection with the electrical rupture of gaseous insulators have been thoroughly investigated by J. J. Thomson, J. Stark, J. Townsend, J. B. Whitehead, F. W. Peek, Jr., and many others, the nature of the breakdown in solid and liquid insulating materials has up till now remained in complete obscurity.

According to the prevailing opinion the rupture takes place at the moment when the density of the electrical field exceeds a certain limit at any point in the insulator. This is called the electrical strength of the material and is based on a reasoning analogous to that which gave rise to the theory of mechanical resistance against a breakdown.

However, there are recorded observations about the rupture of insulating materials which one is unable to reconcile with the general opinion that the rupture takes place as soon as the electric field strength exceeds the critical point. I made such an observation during the year 1905, and as it made me at that time doubt the correctness of the existing theories I shall endeavor to discuss it here.

Fig. 1 shows the cross-section of a concentric cable. A number of these cables, with various ratios of R to r, that is the ratio of the outside diameter of the insulation to the inside diameter, were measured for breakdown voltage. From this the maximum field density E, existing along the radius r was calculated. The result was that as long as the ratio $R:r$ did not exceed a certain limit, approximately 2, the maximum field density was equal to that which existed when rupture took place on flat plates of the same material, namely $E = 10{,}000$ volts per mm. For large values of R to r, however, the rupture took place after E had increased to about 15,000 volts per mm.

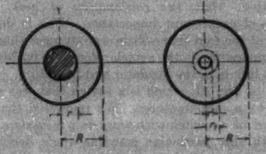

Fig. 1

Some one immediately suggested as an explanation that the inner layers of the insulation had been ruptured after E had exceeded 10,000 volts, and that as a result the diameter of the conductor had in effect increased from r to r_1, with a consequent decrease in the maximum field density even while the tension remains the same.[1]

In order to test this assumption a cable-section was subjected a certain length of time to a tension nearly reaching the limit, so that at least the inner part of the insulation from r to r_1, was subjected during this period to a field density far in excess of the rupture limit. Then the paper insulation was unwound till the supposedly ruptured part from r to r_1 was reached. What remained of the cable section was then provided with a metal cylinder, and subjected to an electrical tension. The test showed it to be perfectly intact and it ruptured only at the normal limit, (10,000 volts per mm.). It was thereby proved that such a material can be subjected without disadvantage to an electrical field density far above the normal.[2] This one and other tests show, therefore, that the analogy generally assumed between electrical and mechanical strength does not exist. Moreover I dare claim that this assumed analogy has not in the least promoted a clear understanding of the electrical phenomena; on the contrary it has been an obstacle in the way of understanding the true nature of things.

I observed during the numerous rupture tests which I conducted some years previously that the material prior to rupture heated up considerably in some places, while other parts remained comparatively cool, and that the rupture always took place at such a spot after it had become hot. If the current is interrupted before the rupture has taken place, and the heated spot is examined after cooling down, it is found that the electrical qualities of this spot do not differ materially from the spots which remained cooler.

Why then does the rupture occur at the heated spot?

It is a well known fact that the resistance of the insulation decreases rapidly with increasing temperature. The hot spots therefore take up a larger current than the adjoining cooler spots, which are subjected to the same tension. It is evident that the hot places receive more energy than the cooler ones, with the result that the temperature difference further increases. It is easy from this to picture that at a certain tension an

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[1] Similar experiments were undertaken later by M. Klein, E. T. Z. 1913 p, 851.

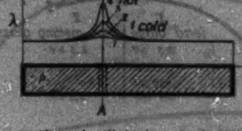
[2] A. Russel, in a paper in the JOURNAL of the I. E. E., Vol. 40, 1907, p. 6 has developed a theory based upon the same assumption.

unbalanced condition takes place, and the hottest spot finally burns.

This is my theory of the physical occurrences at electrical ruptures of solid insulators.

It could be said that although this analysis is apparently simple, at first it seemed difficult to draw comprehensive conclusions as to the occurrence of ruptures depending on various factors. However, this did prove possible, and I will show in the appendix how by making certain simple assumptions this proved to be the case.

For the present time I wish to point out only the general lines of the theory and the most important conclusions drawn from it, and at the same time to show in just what manner I have endeavored to disclose the nature of the rupture phenomena by experiment. The work is not as yet concluded, but the data already obtained are sufficient to support the conception represented in this paper.



A • spot with higher conductivity

FIG. 2

Take a plate P of insulating material (Fig. 2) provided on both sides with electrodes. This plate will not possess the same electric conductivity all through its section, but on the contrary, due to the lack of homgeneity in the material the conductivity will be higher in some places than others. Let A be such a place.

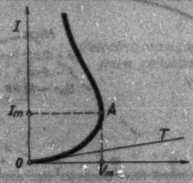


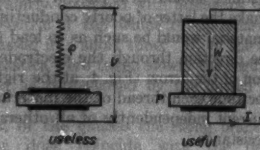
FIG. 3

Curve 1 may represent the original distribution of conductivity in the plate section. Subject the plate now to a certain potential, and a current will traverse the plate. The current density will be a little higher in A than elsewhere. The insulating plate is heated by the current, and to a larger degree in A than elsewhere. Now as the conductivity increases directly with increasing temperature, the conductivity distribution of the plate under electrical tension, will be represented by curve 2. Note the increase at A over curve 1. If, at the increased temperature at A, the heat conducted to the surroundings of A is equal to the heat created in A, curve 2 will remain stable. If the opposite is true, then the curve will become still more pointed. This also may happen, (curve 2 representing a stable distribution) if the electrical tension V is increased (curve 3). Finally a condition occurs represented by curve 4, during which the created heat grows faster than the heat conducted to cooler parts, and the temperature grows more and more rapidly and similarly the conductivity, and the current, until the rupture takes place at A.

The above leads to consideration of a thin thread of the insulating material.

The initial resistance of the thread may be R. As long as the voltage V remains small, the heating according to Joules law remains small and the resistance constant.

The current voltage characteristics (Fig. 3) are thus a straight line $O\ T$. With increasing tension the thread heats up and the resistance decreases, consequently the current increases more rapidly in proportion to the tension. Finally a point will be reached when the resistance decreases further, without a corresponding increase in the voltage. This is the rupture point and the voltage V_m, is the breakdown voltage.



useless useful

FIG. 4

It is easy to determine by experiment the characteristics up to point A. The portion above A represents the unstable condition, and this is passed at an immense speed and can therefore not be observed.

After I had made the above analysis, I was, of course, tempted to make an experimental test. At first I could see no possible way of determining the portion of the curve above A. Other work took up my time and interest and it was not until I began investigations on the nature of dielectric losses and their laws, that my attention was again directed to the rupture problem. In 1914 when these investigations were concluded[3] I found time to experiment again with the rupture phenomena.

I had previously tried to disclose the characteristics of the curve above A by means of connecting a high resistance in circuit with the plate of insulating material (Fig. 4, at the left.)

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[3] 3. The theory of imperfect dielectrics, "Annalen der Physik, Vol. 40, 1913, p. 817. "Dielectric Viscosity," *Elektrotechn. Zeitschr.* 1913, p. 1279. "Explanation of the Dielectric After-Effect according to "Maxwell's Theory," *Archiv. f. Elektrotechnik*, Vol. 2, 1914, p. 371. Dielectric properties of some insulating materials," *Archiv. f. Elektrotechnik*, Vol. 3, 1914, p. 67.

I hoped that this resistance would perform in a manner similar to the stabilizing resistances of electric arcs, and thus allow an observation of the points of the curve above *A*. This, however, proved futile.

Even when using very high resistances and corresponding high tensions V_o, it was impossible to reach beyond point *A*. Always a complete rupture took place, as soon as *A* was reached.

The following explanation was found for this unexpected result:

The insulating body with its two metal electrodes forms a small plate condenser.

At point *A*, where the insulating material begins to give way, an amount of energy $1/2\ C V_m^2$ is stored in this condenser, *C* being the capacity of the condenser. This stored energy jumps at once at the weak spot and feeds during a short time a much stronger current than the ordinary source of current, could supply over the resistance.

In other words the energy required for rupture *i. e.*, local burning, is supplied by the electrical field energy of the condenser. I found the following way out of this difficulty.

The resistance should form part of the electrode itself, *i. e.*, make the latter of poorly conducting material. The best material would be such as to lead the current only in one direction through the electrode that is in the direction of the arrow (Fig. 4, at the right). With such an electrode each thread of the material would be fed with current independently of all others through a constant resistance.

The current supply of a weak thread, could not come from adjoining parts, as occurs with metallic electrodes just before rupture.

The material which, most nearly meets the desired specification, is wood although it is not quite perfect.

Its conductivity across the grain is not zero, but it is considerably smaller than in the direction of the grain.

By means of impregnation and the choice of suitable kinds of wood the required range of resistances can be procured.

Thus, in the beginning of 1914, it was possible, after overcoming several experimental difficulties, to plot curves for the rupture characteristics of different kinds of paper, gutta percha and rubber. They showed the expected form of Fig. 3. Unfortunately the experiments had to be discontinued when the war broke out and could not be resumed until 1919. Since then I have been graciously assisted by Messrs. Stahl, Kupfmuller, Mitzel, Dr. Dieterle and Ludwig in carrying out the experimental work.

The method of recording the characteristics was as follows:

The *V I* curves were taken with the arrangement shown in (Fig. 4, at the right) both with the wood electrode alone and with plate *P* inserted.

The difference of the tensions read for the same current in both cases is the tension of the insulating plate *P* belonging to this current.

As source of current we used partly a rectifier fed with 500 cycles alternating current, and partly an electrostatic induction machine.

In order to avoid using too high tensions, *V*, the insulating material was tested in the form of thin plates (in some cases down to a few hundredths of a millimeter). The tests covered so far include different kinds of paper, oiled paper, paraffined paper, gutta percha, vulcanized rubber, cellon and similar materials, glass and mica.

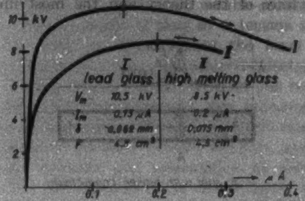


FIG. 5

Due to lack of space, I can give only a short report of the tests. Therefore, I shall confine myself to a description of the most important results in general.

In Fig. 5 there are represented the breakdown characteristics of two different kinds of glass (lead glass and high-melting glass). Fig. 6 shows the characteristic of mica; Fig. 7, those of cellon (two plates of different thickness); Fig. 8, that of another product manufactured from cellulose. In the latter case, the wooden electrode had been covered with tinfoil. This experiment therefore relates to an arrangement as represented at the left of Fig. 4. According to the remarks formerly made, we observe the current suddenly increasing as soon as the breakdown voltage V_m is reached, while the tension diminishes to a small fraction. A hole burnt into the sample was found by inspection after the experiment.

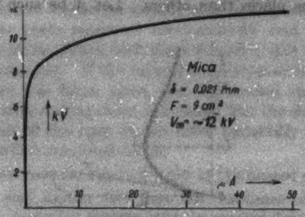


FIG. 6

The following statement has been proved to be of general validity:

The rupture voltage is in direct proportion to the thick-

ness of the tested material and independent of the size of the plate.

As an example, the data from a series of tests with gutta percha are shown in Fig. 9.

Of course, the particular characteristics of different samples of the same material do not coincide exactly due to the lack of homogeneity of any dielectric, and therefore the preceding statement relates to the mean voltage obtained from a number of equal tests.

When testing for ruptures with the usual metallic electrodes, the rupture voltage, as we know, grows slower than proportional to the thickness of the plates. This results from the distortion of the dielectric field on the edges of the plates. On the other hand with the method herein described the edge effect has very little influence, because the current flowing at the edges is only a very small portion of the total current, plotted in the characteristic curve.

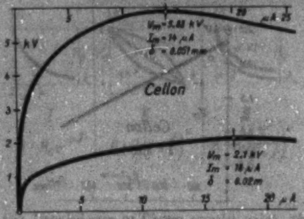


FIG. 7

If the characteristic curve of a transparent material is carried on to currents beyond the rupture point, and the material is inspected under a magnifying glass or a microscope, it is often found disturbed at a large number of points and rendered dull. The characteristic obtained is therefore, the *mean* characteristic of all these "spoiled" paths. It may be understood that the material at these places has been spoiled by excessive current. When decreasing the tension from point B downward (Fig. 10, at the left), the curve 2 is obtained. This curve however, contains also the current of those paths, which were heated only and thus made better conductors, but not burnt.

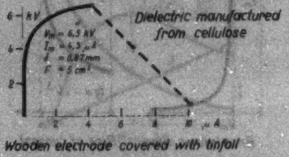


FIG. 8

By waiting until the material has cooled off, and then again taking the characteristics, curve 3 is obtained.

On the other hand if the characteristic is taken for the first time up to a point B, below the maximum, and then down again, the two characteristics practically come together. (Fig. 10, at the right). The fact that they do not cover each other entirely, demonstrates that several particularly bad spots had already undergone damage during the rising curve.

The characteristic shown in Fig. 11, relating to a thin sheet of vulcanized rubber may be taken as an example, representing the case just mentioned.

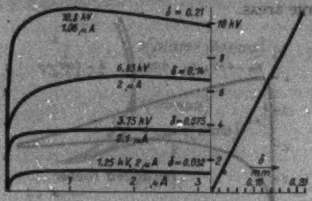


FIG. 9

The hump on the characteristic curve of oiled paper (Fig. 12) is by no means due to an error in the test, but has been regularly observed with numerous tests with the said dielectric if the whole of the characteristic curve was passed in a short time. If, on the contrary, the characteristics were taken slowly the regular shape was obtained as represented by the dotted curve in Fig. 12.

With most of the glasses the rising branch of the characteristic does coincide with the descending branch (see Fig. 5). In such cases the characteristic curve may be passed several times up to points far beyond the rupture point without doing any damage to the dielectric. Part of the glass plates cracked when some point of the curve beyond the breakdown voltage was reached; that was obviously due to overheating of particular spots of the plates.

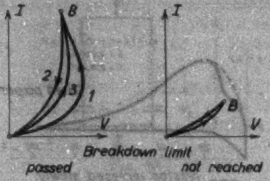


FIG. 10

As a result of the lack of homogeneity of the material, the rupture voltage determined as usual with *metallic electrodes* is evidently depending on the electrode area. Each rupture test only gives the rupture voltage of the worst spot of the tested sample.

If the same number of tests is made on small and large areas, the chances of finding bad spots in the latter case is greater, and consequently with large areas a lower mean value of rupture tension is arrived at.

Geweeke & Krukowski[4] have proved the correctness of this assertion. They made n times as many tests with small electrodes of area f as with large electrodes of area $n \times f$; then they took from each series of n successive tests with small areas the lowest rupture voltage. The mean value of all these minimum voltages was found equal to the mean value of all the rupture voltages with large areas.

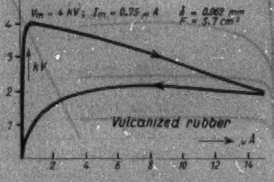


Fig. 11

I repeated these tests together with Mr. Stahl and found the same results. Mr. Stahl worked out a method of calculation, to determine the mean rupture voltage for any larger area from the distribution curve of the rupture voltages with small areas. Mr. Stahl's method is based upon the calculation of probabilities, and his results were also found in conformity with the test results. With the wood electrode test the mean breakdown voltage is determined, and this, of course, is independent of the area of electrodes except perhaps for very small areas.

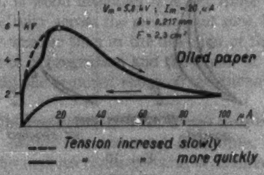


Fig. 12

It appeared desirable to follow through mathematically the thought that an insulating plate is ruptured by the overheating of the material caused by the current flowing through a weak spot. It could be hoped to find in this way certain relations which could be tested experimentally.

I do not wish to take up much of your time by producing here mathematical deductions,[5] but shall briefly give my considerations and the conclusions derived.

If we increase the voltage slowly so that thermic equilibrium is maintained in the material, the electrical energy delivered to one fibre $R\,I^2$ must equal the amount of heat energy per second conducted from that fibre to the cooler surrounding parts of the material.

If we know the relation of the resistance R of the fibre to the temperature, we are able to calculate the characteristic current-potential curve of the fibre (V = function of I) by means of the mentioned equilibration condition.

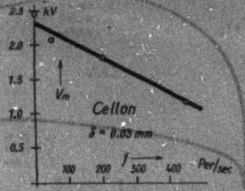
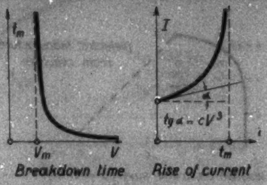


Fig. 13

It is well known that the resistance of insulating material decreases rapidly with increasing temperature, and that we can easily express this relation through some exponential or other function of the temperature.

With these and similar assumptions I have succeeded in calculating the characteristics of a material I. E., to determine the curve by means of the electrical and thermal constants of the material.

It is remarkable that the result of these calculations and the considerations mentioned further on depend very little on the specific assumption which has been made about the decrease of the resistance with increasing temperature. The shape of all these calculated characteristics conforms fairly well with the observed ones; and the theory is proved that the rupture voltage is proportional to the plate thickness.



Breakdown time Rise of current

Fig. 14

Insulating material subjected to *alternating voltage* is heated not only by the current, but also by the dielectric losses. These are approximately proportional to the frequency and the square of the tension. If we consider these dielectric losses in the heat equilibrium condition, we find that the rupture voltage with alternating current must be smaller than with direct current. With low and medium frequencies it decreases in a linear function of the frequency (Fig. 13). This law was corroborated by our tests, which up to now covered frequencies from 0 to 500 cycles.

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[4] *Archiv. f. Elektrotechnik*, Vol. 3, 1914, page 63.

[5] See the Appendix.

Until now, it has been generally assumed that the maximum or peak value of the voltage curve would be responsible for the rupture. According to the overheating and burning theory of rupture, it is the *effective tension* which might be expected to be mainly responsible for the breakdown. There would exist, therefore, a very distinct difference between gaseous and solid dielectrics. This is a highly important conclusion of the theory, and it had to be borne out by test. By elimination of parts of a sine wave, a tension curve with a low effective value but a high peak was generated. The effect of this tension on the insulating material was very approximately proportional to the effective value and the short-lived high peak could be a considerable multiple of the rupture voltage, without causing a rupture.

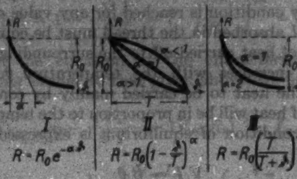

FIG. 15

Following these tests, we made tests with short single shocks, similar to those used by Mr. Peek in testing spark gaps. These shocks were created by a non-periodic condenser-discharge. In this case the effective value of the impulse, $\int_0^\infty V \; d\,t$ apparently governs the effect on the insulating material. These tests, however, are not concluded as yet.

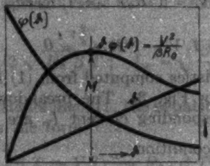

FIG. 16

If the tension exercised on a piece of insulating material is increased rapidly, the breakdown does not occur instantaneously, as soon as the rupture voltage is reached. We can, therefore, subject the material for a short time to a tension V, which exceeds the normal rupture tension without a rupture taking place.

For each voltage V, exceeding the breakdown voltage we find a time t_m, which elapses before the rupture takes place. (Fig. 14, at the left). The retarding of the rupture comes from the fact that with each temperature increase, heat energy has to be stored in the insulating material. This of course requires time.

The theoretical treatment of this problem showed the remarkable fact that the form of the curve (Fig. 14) does not depend on the kind of the tested material, if the scales of time and voltage are properly chosen. This means that the ratio of the heat capacity to the heat conductivity of the material has to be taken as unit of time and the breakdown voltage as the unit of voltage.

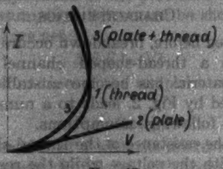

FIG. 17

The current traversing the insulating material increases with the time as shown in Fig. 14, at the right. This is another relation which may be calculated theoretically.

An interesting conclusion of such calculation is that the increase of current in the beginning is proportional to the third power of the tension V, namely: $\tan\alpha = \text{const.}\ V^3$. The truth of this relation was proved by our tests.

According to the common theory, *i. e.* the so-called maximum electrical strength theory an insulating material exposed to a non-uniform electrical field should rupture as soon as the field—strength has passed a certain limit anywhere within the dielectric. But this conclusion has proved to contradict experience in many cases and may also not be justified by the author's theory. The dielectric is capable of withstanding an overstraining without damage, supposing that the less strained parts of the dielectric contained in the path of the current prevent the latter from increasing excessively. Rupture does not occur before the condition of the *whole* path of the current has become unstable.

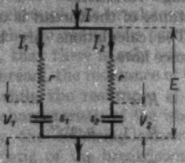

FIG. 18

The conformity of all these theoretical conclusions to the observed tests, may, I believe, serve as a strong support, for the correctness of the idea that the electrical rupture of solid dielectrics is a phenomenon of overheating by current.

By this explanation the breakdown phenomena, mysterious as they have been hitherto, are shown to be the consequence of well-known physical laws and at the same time are opened to numerical treatment.

Appendix

1. CALCULATION OF THE BREAKDOWN-CHARACTERISTICS

As explained before, breakdown occurs as soon as the condition in a thread-shaped channel through the insulating material has become unstable. This idea, as represented by Fig. 2, leads to a numerical calculation by the following assumptions.

a. Only the resistance of the thread-shaped channel shall vary with the voltage while the resistance of the remainder of the dielectric is supposed to be independent of the voltage variations.

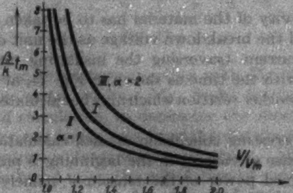

FIG. 19

b. The resistance of the thread is a function of the temperature. The calculations are based upon the following resistance laws:

$$R = R_0 e^{-\alpha\theta} \tag{I}$$

$$R = R_0 (1 - \theta/T)^{\alpha} \tag{II}$$

$$R = R_0 \left(\frac{1}{T + \theta} \right)^{\alpha} \tag{III}$$

θ = temperature of the thread above that of the surrounding parts of the insulator; R_0 = resistance of the thread at the initial temperature ($\theta = 0$), R = resistance of the thread at the temperature θ, α, T = constants.

By the Law I the resistance R decreases with increasing temperature according to an exponential function (Fig. 15, at the left), but does not vanish for any finite value of the temperature.

By the resistance Law II, R vanishes at a finite temperature T, which may be called the burning temperature of the insulating material. According to the value of the exponent α, the resistance decreases in a linear manner ($\alpha = 1$), or with slackening ($\alpha > 1$), or with increasing speed ($\alpha < 1$), see Fig. 15.

According to Law III, the resistance decreases continuously with the temperature, the rate of diminution being the larger the higher the exponent α is chosen (Fig. 15, at the right).

For most of the dielectrics investigated until now, the resistance Law III seems to give the best approximation to the actual variation of the resistance with the temperature.

c. If the voltage V be increased so slowly that the stationary condition is reached for any value of V, the power $V\,I$ absorbed in the thread must be equal to the quantity of heat carried off to the surroundings. This quantity increases with the temperature θ. If we suppose the heat to be carried mainly by conduction, the flow of heat will be in proportion to the temperature, and the condition of equilibrium is expressed by the equation

$$V\,I = \beta\,\theta \tag{IV}$$

β being the coefficient of heat conduction. In the case that radiation of heat is to be taken into account, the flow of heat from the thread to the surroundings will increase with a higher power of the temperature, according to the equation

$$V\,I = \beta\,\theta^{n} \tag{V}$$

$$n > 1$$

The following considerations are confined to the equation (IV), the results obtained in this way being in sufficient agreement with the observed data.

The equation of the $V\,I$—characteristics is obtained by eliminating the temperature θ from (IV) with the aid of the resistance law.

By Law 1:

$$1/R = I/V = 1/R_0\, e^{\alpha\theta} = 1/R_0\, e^{\frac{\alpha}{\beta} V I}$$

or

$$f(V, I) = I/V - 1/R_0\, e^{\frac{\alpha}{\beta} V I} = 0 \tag{1}$$

The characteristics computed from (1) have the shape represented by Fig. 3. The breakdown voltage V_m and the corresponding current I_m are obtained from the maximum condition

$$\frac{\partial f}{\partial I} = 0, \text{ for } V = V_m,\ I = I_m \tag{1a}$$

in connection with the equation of the characteristic curve

$$f(V_m, I_m) = 0 \tag{1b}$$

From (1), (1a), (1b), we get

$$1/V_m - \alpha/\beta\, V_m/R_0\, e^{\frac{\alpha}{\beta} V_m I_m} = 0$$

$$I_m/V_m - 1/R_0\, e^{\frac{\alpha}{\beta} V_m I_m} = 0$$

and further

$$\left.\begin{aligned} V_m &= \sqrt{\frac{\beta R_0}{\alpha e}}\,; \quad I_m = \sqrt{\frac{\beta e}{\alpha R_0}} \\ R_m &= V_m/I_m = R_0/e = 0{,}36\, R_0 \end{aligned}\right\} \tag{2}$$

β and R_0 are both in direct proportion to the length of the thread, *i. e.* to the thickness of the insulating material. Consequently the *breakdown voltage* V_m *is in direct proportion to the thickness of the dielectric,* and the current I_m is independent of the thickness.

Supposing the *resistance law II*, we get

$$1 - \theta/T = (R/R_0)^{1/\alpha} = \left(\frac{V}{I R_0}\right)^{1/\alpha}$$

But from (IV) $\theta = \frac{V I}{\beta}$ and

$$f(V, I) = 1 - \frac{V I}{\beta T} - \left(\frac{V}{I R_0}\right)^{1/\alpha} = 0 \qquad (3a)$$

(3a) is the equation of the characteristics. By a reasoning similar to that given above, we find

$$\left(\frac{\partial f}{\partial I}\right)_{V_m, I_m} = -\frac{V_m}{\beta T} + (V_m/R_0)^{1/\alpha} \cdot I_m/\alpha^{\frac{1+\alpha}{\alpha}} = 0$$

$$(V_m, I_m) \qquad = 1 - \frac{V_m I_m}{\beta T} - \left(\frac{V_m}{I_m R_0}\right)^{1/\alpha} = 0$$

$$V_m = \frac{\alpha^{\alpha/2}}{(1+\alpha)^{\frac{1+\alpha}{2}}} \sqrt{R_0 \beta T};$$

$$I_m = \frac{(1+\alpha)^{\frac{\alpha-1}{2}}}{\alpha^{\alpha/2}} \sqrt{\frac{\beta T}{R_0}} \qquad (3b)$$

$$R_m = V_m/I_m = R_0 \left(\frac{\alpha}{1+\alpha}\right)^{\alpha}$$

As before with the resistance law (I) V_m is in direct proportion to the thickness of the dielectric, while I_m is independent of it.

With the special value $\alpha = 1$ (linear decrease of resistance).

$$V_m = 1/2 \sqrt{R_0 \beta T}; \quad I_m = \sqrt{\frac{\beta T}{R_0}} \qquad (3c)$$

With the *resistance law III*, the equation of the characteristic takes the form

$$(V, I) = V(\beta T + V I)^{\alpha} - R_0 (\beta T)^{\alpha} I = 0 \qquad (4a)$$

By proceeding in the same way as before, we obtain the expressions

$$V_m = \frac{(\alpha - 1)^{\frac{\alpha-1}{2}}}{\alpha^{\alpha/2}} \sqrt{R_0 \beta T} \qquad (4b)$$

$$I_m = \frac{\alpha^{\alpha/2}}{(\alpha - 1)^{\frac{\alpha+1}{2}}} \sqrt{\frac{\beta T}{R_0}} \qquad (4c)$$

As a very remarkable fact we note that V_m and I_m are depending on the thickness of the dielectric, on the initial resistance and on the heat conduction coefficient β by the same functions as in the cases of the resistance Laws I and II.

The special value $\alpha = 1$ gives $I_m = \infty$ and $R_m = 0$; the characteristic approaches asymptotically the value V_m with increasing current. The values of α below 1 are without physical meaning in the theory developed here, as they lead to imaginary values of V_m.

As the three resistance laws *I, II, III* lead to quite similar results, we may imagine the existence of a general law

$$V_m = \text{constant } \sqrt{R_0 \beta},$$

which is independent of the particular resistance law. That this assumption is true can be shown as follows.

From (IV) we get

$$\beta \theta R = V^2$$

Now R is a function of the temperature, and we may put

$$R = R_0 \varphi(\theta)$$

φ being a function of θ with the initial value $\varphi(o) = 1$ and continuously decreasing with increasing temperature (Fig. 16).

From the preceding equations we obtain

$$\theta \varphi(\theta) = \frac{V^2}{\beta R_0}$$

Now the expression on the left side means the product of the ordinates of the curve $\varphi(\theta)$ and the straight line θ and is represented by the curve shown in Fig. 16, having an apex.[6] As the ordinate M of the apex does not depend on β or R_0, we have

$$V_m = \sqrt{M \beta R_0} = \text{const} \sqrt{\beta R_0},$$

q. e. d.

By determinating the breakdown characteristics *experimentally*, the current I observed is composed of the current through the breakdown channel and the current through the remaining part of the dielectric. If we suppose, that there is only one breakdown channel, *i. e.* one thread, the resistance of which depends on the voltage, while the resistance of the remainder is constant, the characteristic of the whole dielectric may be plotted by the following construction (Fig. 17). The characteristic of the breakdown channel is given by the curve 1, and the characteristic of the healthy parts of the dielectric by the straight line 2, the characteristic 3 of the whole of the dielectric is found by adding the ordinates of the curves 1 and 2.

If there are existing more than one weak channel the total characteristic is composed of the individual characteristics in a rather complicated manner. Fig. 18 represents the conditions with two weak channels s_1 and s_2. In series with each one we have the resistance r. With the same total voltage E applied, the two channels take different currents I_1 and I_2 and in consequence are stressed with different voltages V_1 and V_2. But by the experimental determination of the characteristics the total current $I_1 + I_2$ is obtained as a function of a *mean* voltage, V, which is taken as the tension acting upon the weak threads. As the connection of V to the V_1 and V_2 is not known, we may say nothing but that the total characteristic must be an intermediate curve between the individual characteristics.

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[6] The existence of an apex is bound to the condition that, with θ increasing, φ decreases ultimately faster than $1/\theta$ does, which condition is fulfilled in all practical cases.

2. DEPENDENCE OF THE BREAKDOWN VOLTAGE ON THE FREQUENCY

In the preceding considerations the weak thread is supposed to be heated only by the current according to Joule's law. With alternating voltages an additional heating occurs by dielectric losses. These are in direct proportion to the frequency of the current and to the square of the tension. The power produced in a thread of the capacity C amounts to

$$N = \omega\, C\, V^2 \cos\varphi = G\, V^2,$$

ω being the circular frequency, $\cos\varphi$ the power factor of the dielectric and G the dielectric leakance of the thread, $G = \omega\, C \cos\varphi$. In order to simplify the corrections in the preceding considerations required by the dielectric losses, we shall suppose the dielectric power factor to be independent of the temperature. In consequence G is a constant quantity for any given frequency.

The combined resistance, composed of the variable ohmic resistance R of the thread and the leakance G has the value

$$\overline{R} = \frac{R \cdot 1/G}{R + 1/G} = \frac{R}{1 + R\,G}$$

$\overline{R}$ determines the proportion V/I, V being the voltage acting on the thread and I the component of the total current being in phase with V[7]. I is the sum of the ohmic current V/R and the leakage current $G\,V$. In the equation

$$V/I = \frac{R}{1 + R\,G}$$

the resistance law (either I, or II, or III) has to be introduced, the temperature θ being determined according to (IV) by the power $V\,I$ and the heat conduction coefficient β.

With the resistance Law I, we get

$$V/I = \frac{R_0\, e^{-\frac{\alpha}{\theta}}}{1 + G\,R_0\, e^{-\alpha\theta}} = \frac{R_0\, e^{-\frac{\alpha}{\beta} V I}}{1 + G\,R_0\, e^{-\frac{\alpha}{\beta} V I}} \qquad (6)$$

or

$$(V, I) = V + V\,G\,R_0\, e^{-\frac{\alpha}{\beta} V I} - I\,R_0\, e^{-\frac{\alpha}{\beta} V I} = 0 \qquad (7)$$

This is the equation of the characteristic. If we apply the maximum condition

$$\frac{\partial f}{\partial I} = 0, \quad \text{for } V = V_m, \quad I = I_m,$$

$$I_m = \beta/\alpha\, 1/V_m + G\,V_m \qquad (8)$$

The expression at the right of (8) has to be introduced into (7) in order to eliminate I_m. This done the factor

$$e^{-\frac{\alpha}{\beta} V_m I_m} = e^{-1-\frac{\alpha}{\beta} G V_m^2} = 1/e\; e^{-\frac{\alpha}{\beta} G V_m^2}$$

appears. At tensions of the order of V_m the power absorbed by dielectric losses comes only to a small fraction of the power absorbed according to Joule's law. Therefore the exponent $x = \alpha/\beta\, G\, V_m^2$ is small as compared with unity, and in consequence

$$e^{-x} = 1 - x$$

holds very approximately, i. e.:

$$e^{-\frac{\alpha}{\beta} V_m I_m} = 1/e\,(1 - \alpha/\beta\, G\, V_m^2) \qquad (9)$$

With (8), (9) and (7):

$$V_m^4 - \frac{e\,\beta\,(1 + R_0\,G/e)}{\alpha\, G^2\, R_0}\, V_m^2 + \frac{\beta^2}{\alpha^2\, G^2} = 0$$

$$V_m^2 = \frac{e\,\beta\,(1 + R_0\,G/e)}{2\,\alpha\, G^2\, R_0} \pm \sqrt{\frac{e^2\,\beta^2\,(1 + R_0\,G/e)^2}{4\,\alpha^2\, G^4\, R_0^2} - \frac{\beta^2}{\alpha^2\, G^2}}$$

Only the root with the negative sign has a physical meaning as it gives for $G = 0$ the correct value of V_m according to equation (2), while the root with the positive sign leads to $V_m = \infty$ for $G = 0$. Therefore

$$V_m = \frac{e\,\beta\,(1 + R_0\,G/e)}{2\,\alpha\, G^2\, R_0} \left[1 - \sqrt{1 - \frac{4\, G^2\, R_0^2}{e^2\,(1 + R_0\,G/e)^2}} \right]$$

With G small, as supposed, the root may be expanded according to the binomial formula, and nothing but the first term of the expansion need to be retained. By this procedure we get the final expression

$$V_m = \sqrt{\frac{\beta\, R_0}{\alpha\, e}} \left(1 - \frac{G\, R_0}{2\, e}\right) \qquad (10)$$

The first term on the right is the breakdown voltage with $G = 0$ (see equation 2), *i. e.* for direct current. The second term shows the decrease of the breakdown voltage with increasing frequency. In particular it is seen from (10) that V_m is a linear function of the frequency[8], as the same is true for G.

If we start from the resistance Law II or III, the same procedure as before may be followed. The mathematical derivations being of rather little interest only the results are given here.

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[7] The capacitive component of the current does not contribute to the heating of the thread and may therefore be left out of consideration.

[8] Of course the linear law holds only for low frequencies, for which G is small, as supposed.

Resistance law II, $\alpha = 1$:

$$V_m = 1/2 \sqrt{\beta R_0 T} \left(1 - \frac{R_0 G}{4} \right) \tag{11}$$

$$I_m = \sqrt{\frac{\beta T}{R_0}} \left(1 + \frac{R_0 G}{2} \right) \tag{12}$$

Resistance law III:

$$V_m = \frac{(\alpha - 1)^{\frac{\alpha-1}{2}}}{\alpha^{\alpha/2}} \sqrt{\beta R_0 T} \left[1 - \left(\frac{\alpha - 1}{\alpha} \right)^{\alpha} \frac{R_0 G}{2} \right] \tag{13}$$

As before with the Law I, we find a linear decrease of the breakdown voltage with increasing frequency, caused by the dielectric losses (see Fig. 13).

3. Influence of Time on the Breakdown Phenomena

According to the hypothesis (c) in part (1), we have assumed the voltage to be varied so slowly, that a stationary condition is reached for any value V of the voltage. This assumption shall be abandoned now. As an example we shall consider the case of a voltage V larger than the breakdown voltage V_m being suddenly applied to the dielectric at a certain moment $t = o$. We know from experience that the current passing through the dielectric increases continually (see Fig. 14, at the right) until the dielectric breaks down. The time t_m elapsed from the beginning of the phenomenon is obviously the shorter, the larger the voltage V has been chosen in proportion to V_m.

At any time between o and t_m the power $V\,I$ respectively V^2/R absorbed from the thread in which the rupture shall occur has to cover the flow of heat to the surroundings and the amount of heat stored up in the material forming the thread.

As the flow of heat equals $\beta\,\theta$ and the amount of heat stored up per second is expressed by $k \dfrac{d\theta}{dt}$, k being the heat—capacity of the thread, the law of conservation of energy takes the form

$$\beta \theta + k \frac{d\theta}{dt} = V^2/R \tag{VI}$$

R is a function of temperature, as per example, given by (I), (II) or (III).

Before we base further calculations upon one of the particular resistance Laws I, II or III, a general theorem shall be deduced, which is independent of the assumption of any special resistance law.

By differentiating Ohm's equation $I = V/R$ we get

$$\frac{dI}{dt} = -\frac{V}{R^2} \cdot \frac{dR}{d\theta} \cdot \frac{d\theta}{dt} \tag{14}$$

From this expression we may calculate the *initial gradient of current, i. e.* the slope of the tangent on the curve at the right of Fig. 14 at $t = 0$. In this point we have $\theta = o$ and therefore, from (VI)

$$k \frac{d\theta}{dt} = V^2/R_0 \tag{15}$$

The coefficient of resistance—variation with temperature $\left(- \dfrac{dR}{d\theta} \right)$ has, for $\theta = 0$, a certain positive value, say c.

With these terms we get

$$\left(\frac{dI}{dt} \right)_{t=o} = \frac{c}{k R_0^2} \cdot V^3 \tag{16}$$

In words: *The initial current gradient is in proportion to the third power of the voltage applied.*

By using the resistance Law I, we get from (VI) the differential equation

$$\beta \theta + k \frac{d\theta}{dt} = V^2/R_0\, e^{\alpha\theta} \tag{17}$$

We may separate the variables in (17) and then integrate both sides:

$$t = k \int_o^{\theta} \frac{d\theta}{V^2/R_0\, e^{\alpha\theta} - \beta \theta} \tag{18}$$

From (18) the time t that elapses until a certain temperature θ in the thread is reached may be numerically computed without difficulty. With θ the resistance R is obtained from (I); R gives $I = V/R$. In this way the curve at the right of Fig. 14 can be theoretically calculated.

The breakdown time t_m follows from (18) by putting $\theta = \infty$:

$$t_m = k \int_o^{\infty} \frac{d\theta}{V^2/R_0\, e^{\alpha\theta} - \beta \theta} \tag{19}$$

Write (19) in the form

$$t_m = k/\beta \int_o^{\infty} \frac{\dfrac{\beta R_0\, e^{-\alpha\theta}}{V^2}}{1 - \theta \dfrac{\beta R_0}{V^2} e^{-\alpha\theta}} \cdot d\theta$$

and develop the denominator according to the formula of the geometrical series

$$\frac{1}{1-x} = 1 + x + x^2 + x^3 + \ldots$$

$$t_m = k/\beta \int_0^\infty d\,\theta \Big[\Big(\frac{\beta R_0}{V^2}\Big) e^{-\alpha\theta} + \theta \Big(\frac{\beta R_0}{V^2}\Big)^2 e^{-2\alpha\theta} + \ldots \Big]$$

By the application of Euler's well-known Integral we get

$$t_m = k/\beta \Big[\frac{\beta R_0}{\alpha V^2} + 1\,!\, \Big(\frac{\beta R_0}{2\,\alpha V^2}\Big)^2 + 2\,!\, \Big(\frac{\beta R_0}{3\,\alpha V^2}\Big)^3 + \ldots \Big]$$

According to (**2**), we have $\beta R_0/\alpha e = V_m^2$. We introduce this term in the foregoing equation and obtain the final expression

$$t_m = k/\beta \,[e\,(V_m/V)^2 + 1\,!\,(e/2)^2\,(V_m/V)^4 + 2\,!\,(e/3)^3\,(V_m/V)^6 + \ldots] \qquad (\mathbf{21})$$

The expression within the brackets depends on (V_m/V) exclusively and may be easily calculated as the series converges rapidly. (**21**) is represented by Fig. 14 at the left.

A very remarkable result follows immediately from (**21**): *If we plot $\beta t_m/k$ against V/V_m, we obtain the same curve from any kind of insulating material.* In other words: *The breakdown curve $t_m = f(V)$ for a certain dielectric may be transferred into the curve for any other dielectric simply by changing the scale.*

The theorem just mentioned has been obtained by assuming the resistance Law I. But we shall find it true with each of the other resistance Laws II and III too.

With the Law II the deductions shall be confined to the case $\alpha = 1$, according to

$$R = R_0\,(1 - \theta/T)$$

The calculations are omitted, as they do not show anything of interest; the result is

$$t_m = k/\beta \frac{2 \text{ arc sin } (V_m/V)}{\sqrt{(V/V_m)^2 - 1}} \qquad (\mathbf{22})$$

By (**22**) $t_m\, \beta/k$ is, as before, *a function of V/V_m only.*

In the case of the resistance Law III we have

$$\beta\,\theta + k\frac{d\,\theta}{d\,t} = V^2/R_0\,(1 + \theta/T)^\alpha$$

We put, for abbreviation

$$\theta/T \qquad (\mathbf{23a})$$

and

$$\frac{\beta\, T\, R_0}{V^2} = A \qquad (\mathbf{23b})$$

By introducing these terms, separating the variables and integrating:

$$t_m = k/\beta \int_0^\infty \frac{A\,d\,\eta}{(1+\eta)^\alpha - A\,\eta} \qquad (\mathbf{23})$$

By (**48**):

$$A = (V_m/V)^2 \frac{\alpha^\alpha}{(\alpha - 1)^{\alpha - 1}} \qquad (\mathbf{23c})$$

Again we find, according to (**23**) *$\beta\, t_m/k$ to be a universal function of the proportion V/V_m.*

For arbitrarily given values of α, the integral on the right of (**23**) can only numerically be computed. But for $\alpha = 2$ it may be expressed by known functions:

$$\left.\begin{aligned} t_m = k/\beta \frac{A}{\sqrt{A - 1/4\,A^2}} \Big[\pi/2 - \text{arc tan} \frac{1 - 1/2\,A}{\sqrt{A - 1/4\,A^2}} \Big] \\ A = 4\,V_m^2/V^2 \end{aligned}\right\} \qquad (\mathbf{23d})$$

In Fig. 19 the relations given by equations (**21**), (**22**) and (**23d**) are represented for the purpose of comparison. Table I contains the numerical values within a larger range.

TABLE I

V/V_m	$\beta t_m/k$		
	Resistance Law:		
	I	II	III
1	∞	∞	∞
1,11	5,805	4,625	9,26
1,25	3,133	2,473	4,95
1,43	2,055	1,520	3,12
1,67	1,310	0,965	1,93
2,00	0,823	0,604	1,21
2,50	0,490	0,359	0.7186
3,33	0,261	0,192	0.3844
5,00	0,1115	0,0822	0,1642
10,00	0.0274	0,0201	0,0403

The values below III are very nearly twice as large as the corresponding values below II, while the values below I differ from those below II approximately by the factor 1.35. According to these relations, each of the 3 curves in Fig. 19 may be turned into the other one simply by changing the time-scale. In consequence it is impossible to decide only by breakdown trials which particular resistance law holds good. This would require an independent determination of the thermical constant k/β.

With a proper time scale the theoretical curves represent the observed data as well as might be expected if the heterogeneousness of the dielectrics and the corresponding dissemination of the breakdown voltages are taken into account.

Discussion

D. W. Roper: As I understood Dr. Wagner's remarks, he says that practically all dielectric stress failures are dielectric loss failures. That is, the rupture of the insulation is preceded by a localized heating of the insulation due to the passage of the current through the insulation, and that occurs always, except in the case of a very high voltage suddenly applied.

There is one other point about which I would like to inquire. I understood him to state as one of his conclusions that the rupture voltage was proportional to the thickness of insulation. At that time he was discussing tests between plates. Does that also apply to the insulation in cables or in case of a round conductor? And if not, what is the law connecting the rupture voltage to the thickness of insulation on a round conductor?

R. E. Hellmund: We are certainly indebted to Dr. Wagner for the new idea regarding the cause of electric breakdowns. As he himself mentioned, there is hardly anything in the electric art about which we know as little as about the breakdown of solid materials. I surely hope that the various representatives of universities that are present will take up this subject and study it, so that we may obtain a better knowledge of insulation breakdowns.

I might mention that Dr. J. C. Shrader made numerous tests in the Westinghouse Research Laboratory regarding the law between voltage and the currents flowing through the insulation. They practically agree with Dr. Wagner's except that Dr. Shrader's tests go only up to the point of breakdown. In all cases he gets a straight line and a bend just before the breakdown. These tests have been made for a great many different materials and check out in all cases. It has been proposed to apply such curve tests carefully to electrical machines, in order to determine their breakdown point. That is, instead of going to the actual burn-out or breakdown, it is proposed to simply go to the bend in the curve and thus determine, approximately, the breakdown point, without destroying the machine insulation.

K. W. Wagner: I made the experiment with cables and at that time I didn't have much care for the time taken for breakdown. As I mentioned before, these experiments will be carried out later, and I will study the influence of the time on the breakdown.

This curve showing the time required for breakdown at a certain voltage is, as I mentioned, a universal one. If we take both a unit of time and a unit of voltage, of course the shape of this curve depends somewhat on the assumption made if the law governing the insulating resistance depends on the temperature. But it depends, in fact, on a very little proportion of this, and I made several assumptions on the dependence of the resistance on the temperature and exponential function and several others containing powers of the temperature, but all of these if the testing plates are put in give the same shape of the curve.

On the question of the breakdown voltage depending on the thickness of the insulation of concentric cables or three coil a-c. cables, I am not able to answer that question at this time. My experiments on the thickness were only made for plates.

Charles P. Steinmetz (by letter): The pyro-electric theory of insulation failure described by Dr. Wagner is fully corroborated by the conclusions from Mr. Hayden's and my investigations on insulation, and it therefore was of great interest to us to compare notes with Dr. Wagner during his visit. His ingenious method of carrying the volt-ampere characteristic of solid insulation beyond the so-called "breakdown point," by using wooden terminals, was new to us. We secured the required distributed current limitation by testing the sample between thin sheets of an insulation of higher dielectric strength and smaller temperature effect, such as mica, or by calculation from the temperature resistance curves of the material taken at high voltage, or by using a filamentary thread of insulation. The last method has the advantage of giving the true voltage characteristic, while the other methods give only an average characteristic. It has however the disadvantage to be limited to those few insulators, which have a relatively low resistivity, such as the material of the Nernst lamp glower.

In the mathematical appendix Dr. Wagner shows that, under certain conditions, the breakdown voltage is proportional to the thickness of the insulation, if the breakdown is a pyro-electric effect. This, however, does not mean that the breakdown cannot be a pyro-electric effect, if the breakdown voltage is not proportional to the thickness of the dielectric, but, as commonly the case, increases at a slower rate.

Dr. Wagner's conclusions are based on the assumption of the "hot spot" as a filament connecting the terminal (Fig. 2 of his paper) and conducting its heat away exclusively tangentially, into the dielectric, but not towards the terminals. With wooden terminals of low heat conductivity, this would be the case.

With metal terminals of good heat conductivity however, considerable heat conduction might occur also towards the terminals, especially if the hot spot is not filamentary, but its diameter of the same magnitude as the thickness of the dielectric, as would more probably be the case in a laminated dielectric. In such case, most of the heat may be conducted towards the terminals.

Assuming therefore, as the extreme case, that all the heat produced at the hot spot forming in the insulation, is conducted towards the terminals. Then by similar calculation as those given by Dr. Wagner for the extreme case, we find that *the breakdown voltage is proportional to the square root of the thickness of the dielectric.*

In general, heat will be conducted away transversely, towards the terminals, as well as tangentially, into the dielectric, and depending on the proportion of the heat conducted tangentially and heat conducted transversely, the breakdown voltage would vary with the thickness somewhere between the first power and the square root.

In concluding, I wish to say that the pyro-electric theory of insulation breakdown does not mean that the effect and the importance of dielectric hysteresis and ozonization losses, with alternating voltage, are overlooked. The conductivity of the insulation, which progressively increases by the temperature rise at the hot spot, must be understood as the effective conductivity, including the dielectric hysteresis, ozonization effect, etc.

Selection of Electrical Apparatus for Cranes

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Review of the Subject.—*This paper is intended to assist crane designers and electrical engineers in mills and factories to select the proper size and kind of motor by mathematical calculation from given data, and refers particularly to the electric overhead traveling crane. The paper does not apply to heavy duty cranes which undergo regular duty cycles, nor to very small hoists such as the monorail hoist. It is hoped that at some future date someone else will write papers on these two kinds of cranes to supplement this paper.*

Cranes are classified here for purposes of reference within the paper. It is then shown how to calculate the power required of a motor for hoisting and how to select the particular kind of motor needed; the same information is given for bridge travel with particular reference to the live loads or accelerating loads, and also for trolley travel.

The paper discusses direct-current motors separately from alternating-current motors. The calculations for each are also given separately.

This is the first of a series of papers covering the field of applications of electrical equipment. This paper is on application of motors to cranes. One will follow by Mr. H. W. Eastwood on auxiliary electrical equipment such as magnetic friction brakes, overload protective panels, and limit switches. To complete the series it is planned to have the third paper on the subject of controller equipment.

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  Class 2, Machine-Shop and Foundry Cranes. (75 w.)
  Class 3, High Duty Cranes. (50 w.)
  Class 3-A, Magnet Cranes.
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Selection of A-C. Trolley Motors. (110 w.)

In the selection of electrical apparatus for crane drives, it is first necessary to consider the various classes of cranes. For reference later, these classes are enumerated below:

Class 1. Stand-by or service cranes which are used in emergencies, and at rare intervals. A typical example is the power-house crane which is used during installation and thereafter only when repairs are made. The apparatus on such a crane should be simple and should be worked to the limit of its capacity. The control should be very accurate for placing large machines even when used by unskilled operators, as this kind of crane is so rarely used that there is no regularly trained operator for it.

Class 2. Machine-shop and foundry cranes, which are always in service and moderately busy. The apparatus on them should be simple but not worked so nearly to the limit of its capacity as in Class 1. There is always a regular operator in attendance and, therefore, the control apparatus does not necessarily have to be so accurate as in Class 1. In this same class belong loading cranes which serve storage yards where infrequent movement of the stock occurs.

Class 3. High-duty cranes such as are used for moving material in steel mills and for loading material into cars from storage yards where stock is frequently moved. On these cranes very strong apparatus is required, and complications are warranted to some extent in order to secure long life of the apparatus. All apparatus should be very conservatively rated.

Class 3*A*. Magnet Cranes. On these cranes the hoist motion must be especially chosen so as to stand two times normal load because sometimes two times normal load sticks to the magnet for an instant while it is separating bars from their neighbors. The bridge and trolley motions must be chosen for frequent round trips, probably 60 trips an hour.

Class 4. Soaking pit, charging and stripper cranes. On these cranes fire-resisting insulation is required on motors, and apparatus should be designed to be mechanically strong, conservative in size and exceptionally safe in operation.

Class 5. Hot metal ladle cranes. These cranes should have fire-resisting insulation and should be extremely conservatively designed.

This article will not discuss various small foundry jib cranes and others of this same kind which are operated by a man on the floor rather than by an operator who rides with the crane.

General Selection of Electrical Equipment. To assist in selecting the general type and arrangement of electrical equipment, Table I has been compiled, in which all the various features to be considered are pointed out.

Calculation of Power for Hoisting. The horse power of the lifting motor depends upon the work done on the load, and the power absorbed in the resulting friction of the gearing, journals and pulleys. This quantity varies to some extent with the number of reductions and the type of gearing. The efficiency of a crane is generally lowest at the test, improving somewhat as the journals and teeth wear down.

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The efficiency of the first or motor reduction with well-made machine-cut spur gears, running in an oil-bath, has been found by trial to be as high as 97 per cent, and may be taken at 95 per cent under ordinary practical conditions. The average efficiency of one reduction of cut spur gears, running dry, is 92 or 93 per cent, and of cast spur gears, running dry, 90 per cent. The loss due to journal friction is generally about 2 per cent for each axle, when properly lubricated. The only other loss in efficiency of any importance is in the snatch block, if there is one fitted to the crane. This quantity is always reduced by using large pulleys and, preferably, small hardened pins, the pulleys being bushed with gun-metal, under which condition the efficiency works out to about 97 per cent.

$$\text{h. p.} = \frac{W \times S}{33{,}000 \times e} \qquad (1)$$

where h. p. = horse power to hoist at full speed.
(All starting resistance short-circuited) (2)

W = weight of suspended load in pounds including tackles (3)

S = speed of hook in feet per minute (4)

e = necessary factor to allow for friction losses in the crane (5)

The value of e varies from 0.25 on low-speed (10 ft. per minute) cranes which use worm gears, to 0.70 for high-speed (75 ft. per minute) cranes which use good cut gears. The over-all mechanical efficiency of a crane can be determined, if the number of reductions and the other particulars are known. Small high-speed cranes have a higher efficiency than larger ones, owing to there being less gearing; thus, in the case of a trolley lifting three tons on a single rope and having two reductions of machine-cut gearing, the first of which runs in oil, the over-all efficiency will be about:

$$\frac{95 \times 92 \times 98 \times 98}{100} = 84 \text{ per cent.}$$

As another example, take a 50-ton trolley having four reductions, the first three of which are machine-cut, the motor reduction running in oil. Then the over-all efficiency will be about:

$$\frac{95 \times 93 \times 93 \times 90 \times 98^4 \times 97}{100} = 66 \text{ per cent.}$$

$$T = \frac{5250 \times \text{h. p.}}{\text{r. p. m.}} \qquad (6)$$

T = Torque on motor shaft required to hoist as in (1) expressed in pounds at one foot radius (7)

r. p. m. = Speed of motor shaft in revolutions per minute with all resistance cut out of the circuit (8)
(This corresponds to S in (4))

$T_1 = T \times e^2$ if no friction brake is used for lowering (9)

where

T_1 = braking torque in pounds at one foot radius required to lower the weight W (10)

The torque to hoist an empty hook or drive it down is about 5 to 30 per cent of the torque required to hoist maximum rated load of the crane. This is due entirely to crane friction.

In addition to the work of hoisting (1) there is the work of accelerating. Most of this work, on cranes lifting at less than 150 ft. per min., is expended on the motor armature and brake wheel. An approximate rule is to assume that the horse power input to accelerate an armature and brake wheel to full speed in one second is equal to the 30-minute horse power rating of the motor for alternating-current induction motors (11); and is equal to one-half the 30-minute horse power rating of the motor for series-wound direct-current motors (12).

A more exact rule is to obtain from the motor manufacturers the weight and radius of gyration of the armature. Then, horse power input to start =

$$\frac{M \times \text{r. p. m.}^2}{1{,}612{,}800 \times t} \qquad (13)$$

where

M is given in (19)

r. p. m. = speed of motor shaft as in (8)

t = seconds used in acceleration (usually not over 2 sec.) (16)

Selection of D-C. Hoist Motors. The general requirements are that the motor shall be enclosed to protect its commutator from dirt, that it shall be as light and easy to start as is consistent with necessary mechanical strength, that it shall be accessible and its parts easily replaceable. The power requirements are for a large torque sustained for only a short time—therefore an especially designed motor for crane service is needed. It differs from a motor which is used for continuous drive in that it requires the mechanical strength of a large motor, the commutating capacity of a large motor, but needs to have only the active electrical material of a small motor. The smaller the active electrical material and the closer it can be located to the armature shaft, the better the motor, because of the lightness and small flywheel effect which are advantageous for a motor that starts frequently and quickly.

Manufacturers of crane motors have given especial attention to the question of commutation either by using large brush area and narrow commutator bars with many windings or by using commutating poles.

When required to meet the modern requirements of dynamic braking control, the motor must be stable and have good commutation when separately excited and when run at a high speed delivering about 50 per cent of the rated torque; and it must show equally good commutation in either direction of rotation without shifting the brushes.

It is advantageous for these motors to have split frames, easily accessible connection cables and brushes, so that the motor can be readily dismantled and repaired in a small cramped space in the quickest possible time.

To select the proper size of motor for crane hoist, determine (a) the maximum horse power to be delivered by the motor, and (b) the usual horse power. The horse power value obtained by adding h. p. (**1**) for a maximum load to h. p. (**13**) (or, for approximate results to h. p. (**11**) or (**12**)) should always be less than the motor's commutating limits. This may be the five-minute rating of the motor if commutating poles are used. By formula (**1**) the horse power delivered under usual operating conditions should be determined. This usual value of horse power determines the ordinary rating of the motor and it should be:

For Class 1 cranes, the 15-minute rating of the motor.

For Class 2 cranes, the 15- or 30-minute rating of the motor.

For Class 3 cranes, the 60- or 90-minute rating of the motor.

For Class 3A cranes, the 90-minute rating of the motor (because of the uncertainty of the load when the magnet attracts too large a piece).

For Class 4 cranes, the 60- or 90-minute rating of the motor.

For Class 5 cranes, the 30-minute rating of the motor.

On large cranes of Class 5, it is customary to use two hoist motors, each of which alone can hoist the total load without exceeding its commutating limits. This excess capacity is warranted on account of the great value of the metal and the necessity of hoisting the load even if one motor is broken down.

Example of Selection of Direct-Current Hoist Motors. Take a crane which usually hoists 10,000 (W) lb. at 20 (S) feet per minute and which has gear efficiency (e) of 0.55. Take the extreme load to be 15,000 lb. Substitute in (**1**).

$$\text{h. p.} = \frac{10{,}000 \times 20}{33{,}000 \times 0.55} = 11 \text{ h. p. to hoist usual load.}$$

Let t in (**16**) be 2 seconds

$$\text{Then} \qquad \text{h. p. } (\mathbf{12}) = \frac{11}{2 \times 2} = 2.75.$$

When the motor has to hoist 15,000 lb. occasionally this will require approximately

$$\frac{15{,}000}{10{,}000} \times 11 = 16.5 \text{ h. p.}$$

Therefore, the usual horse power required will be 11 and on extreme loads (16.5 + 2.75 = 19.25). Choose a motor which will start at 19.25 h. p. and whose 15-, 30-, 60- or 90-minute rating, according to class of crane, is 11 h. p.

Approximate Rule. An approximate rule is as follows:

$$\frac{\text{Tons to be hoisted} \times \text{ft. per min.}}{10} = \text{30-min. rating of motor.}$$

Selection of D-C. Bridge Motors. The general characteristics of these motors should be the same as those described for hoist motors. They should be series wound, totally enclosed and have good commutating characteristics, etc.

Calculation of Power for Bridge Motors. Rolling friction is caused by axle friction and wheel friction. With good lubrication, axle friction in pounds

$$= \frac{0.10 \times (\text{axle radius in inches}) \times (\text{load in pounds})}{\text{Radius of wheel in inches}}$$

With good track, wheel friction in pounds

$$= \frac{0.002 \times (\text{load in pounds})}{\text{Radius of wheel in inches}}$$

The cross shaft runs in several bearings and its efficiency may be around 95 per cent.

The efficiencies of the gears will be as defined above for hoist motions.

The work done by the bridge motor consists of three parts; first, overcoming track resistance and journal friction—sometimes, together, called rolling friction; second, accelerating the crane with load; third, accelerating the motor armature and brake wheel. The first and second items of work above are done through a train of gears and involve gear losses. In the majority of busy cranes, the rolling friction is a small part of the total work and acceleration is the main work. Usually a draw-bar pull of from 20 to 30 lb. per ton will move a well made crane along a good level track. A new stiff crane or a poor track may require 50 or 60 lb. per ton. Acceleration of the crane and armature may require anywhere from 50 to 300 lb. per ton draw-bar pull, depending on circumstances.

Actual tests show that rolling friction may, for different cranes and tracks, vary anywhere from 5 to 50 pounds per ton. However, when a building sags, the draw-bar pull to move a crane may be almost any value and there is no use of trying to calculate it.

Let C = Weight of crane without load in pounds (**17**)

W = Weight of suspended load in pounds (including tackle) (**3**)

N = Revolutions of motor armature which correspond to one foot travel of the bridge along the track (**18**)

$$\text{in other words } N = \frac{\text{r. p. m. of motor}}{\text{f. p. m. of crane}}$$

M = The effective weight of the armature and brake wheel plus an allowance of 5 per cent for gears, expressed in pounds at one foot radius on the armature shaft, *i. e.* the flywheel effect (19)

$$e = \frac{\text{Efficiency of gearing expressed in per cent}}{100} \qquad (20)$$

D = Rolling friction in pounds per ton (21)

V = Free running speed in feet per minute when fully loaded crane is completely accelerated (22)

The easiest way to choose the proper motor is to cut and try. Gear ratio is of vital importance and must be selected to conform to the speed-torque characteristics of the motor.

First determine:

Horse power to propel loaded crane

$$= \frac{V \times D \times \dfrac{C + W}{2000}}{33{,}000 \times e} \qquad (23)$$

As a first trial select a motor whose 30-minute rating is about 30 to 50 per cent above horse power in (**23**). Determine from the motor manufacturer's speed-horse-power curve the speed of the motor when delivering horse power in (**23**). Then determine N in (**18**).

Next determine whether the assumed motor with the assumed gear ratio can accelerate the loaded crane and also the empty crane as rapidly as desired or needed, without exceeding the commutating limits of the motor. The rate of acceleration of empty crane will never need to exceed three feet per second per second; and of a loaded crane two feet per second per second.

Let F = torque in lb. at one foot radius at motor shaft corresponding to horse power in (**23**).

Then $\dfrac{C}{C + W} \times F$ = torque at motor shaft to propel empty crane.

Let A = maximum torque which motor is recommended (by manufacturer) to exert during starting. Commutation and strength will be the limitations rather than heating.

Rate of acceleration in feet per second per second which the empty crane can attain without torque exceeding A

$$= 32.2 \, \frac{A - \dfrac{C}{C + W} F}{\dfrac{C}{2 \pi N e} + 2 \pi N M} \qquad (24)$$

Rate of acceleration in feet per second per second which loaded crane (load being rigid) can attain without torque exceeding A

$$= 32.2 \, \frac{A - F}{\dfrac{C + W}{2 \pi N e} + 2 \pi N M} \qquad (25)$$

It is interesting to note that when the load is hung from the crane by a flexible rope, the motor does not have to start the load as soon as the crane starts. This relieves the motor somewhat. At the first instant of starting, the motor has to overcome rolling friction of total weight of crane and load, and it has to accelerate the crane and armature. As the crane moves away from the load, the load begins to accelerate at a rate far below that of the crane and finally when the crane has moved far enough away from the load, the load is accelerated as rapidly as the crane.

Rate of acceleration in feet per second per second which loaded crane attains at instant crane starts to move (before suspended load begins to move), without torque exceeding A

$$= 32.2 \, \frac{A - F}{\dfrac{C}{2 \pi N e} + 2 \pi N M} \qquad (26)$$

There are four things which tend to limit the rate of acceleration of a bridge motor:

1. Automatic magnetic control can absolutely limit it.
2. Slipping of wheels can practically limit it.
3. Swinging of load can limit it in some cases.
4. Comfort of operator may limit it.

When automatic magnetic control is used, the current-limit devices may be set to a value of current just sufficient to start the crane under the severest working conditions, and if the current is within the working limits of the motor no trouble need be expected on the crane. Of course, trouble can arise if the controller fails to function properly or if the operator "speeds up" the crane by setting the relays for higher current. To safeguard against this last difficulty, it is, of course, necessary to select a motor large enough to make all the speed actually needed. An average acceleration of something like 1 to 1½ ft. per sec. per sec. will be fast enough for cranes which travel at less than 500 ft. per min. or make infrequent starts. Cranes which make regular frequent trips of 50 or 60 ft. every minute or so may need an *average* acceleration of 2 to 2½ ft. per second per second. Cranes which do "stunts" with swinging loads like some bucket cranes, which swing a bucket into a hopper, or hot metal ladle cranes, may need even 3 feet per second per second *peak* acceleration.

When a motor is powerful enough to slip the wheels under full load without exceeding the working limits of the motor, it is out of danger. A simple calculation[1] shows that if one-fourth of the wheels are driven and if these wheels carry one-fourth of the total weight, an acceleration peak of 2 ft. per second per second will just about slip the wheels. Of course, the average acceleration will be less than the peak and will depend on the number of controller steps.[2] If one-half the wheels are driven, the rates of acceleration could be double the above values. Of course, it is possible for a vicious operator to turn his controller on so rapidly after the wheels slip, that the power required to spin the wheels and accelerate the armature will exceed the motor limits; but this is hardly to be expected. Where it is possible for a crane to do its work with only one-fourth of the wheels driven, this drive makes a very practical way of protecting the motor, but where one-half of the wheels must be driven, the motor is not so protected from overload.

Cranes are frequently used for dragging cars and consequently the bridge motors must be large enough to do extra work, when so used. This problem would be something like an electric locomotive problem and will not be discussed in this paper.

Usually when an enclosed crane bridge motor is properly chosen so far as torque and strength are concerned, it is big enough so far as heating is concerned; but this is not necessarily true on rapid-duty cranes. If the crane is running with power on the motor, more than 35 seconds in 100 seconds continuously for 5 hours at a time, heating is liable to be a limitation and the motor manufacturer should be consulted or past experience with similar work should be used.

Selection of Trolley-Motion, Direct-Current Motors. The type of motor should be the same as for hoist and bridge motions and since this motor is "plugged" (or reversed by power when running at high speed frequently) its commutation must be good at double speed and 150 per cent current. Its commutator and windings must be insulated for at least double normal voltage.

Calculation of Power for Trolley Motors.

Let B = weight of trolley carriage less load (**27**)

V = free running speed in feet per minute when fully loaded trolley is completely accelerated (**28**)

Horse power to propel loaded trolley

$$= \frac{V \times D \times \dfrac{B + W}{2000}}{33{,}000 \times e} \qquad (\mathbf{29})$$

Choose a motor whose 30-minute rating is not less than horse power in (**29**).

SELECTION OF ALTERNATING-CURRENT POLYPHASE HOIST MOTORS

For the usual factory crane an open-type motor should be used.

Where metal dust cinders, furnace fires, acid alkali and such unusual conditions are present, motors should be specially insulated and, in some cases, enclosed.

For cement plants the bearings should be enclosed. It has seemed desirable to enclose also the collector rings but there is a considerable physical difficulty in enclosing collector rings on a motor which is equipped with a solenoid brake at one end and gearings at the other end. These difficulties, together with the inaccessibility of enclosed collector rings, have made it a better practical proposition to use open collector rings. It is necessary to clean out the brushes frequently in order to prevent them from sticking.

The slip-ring wound-rotor induction motors are generally used where reduced-speed operation is needed. The single-speed squirrel-cage-rotor type of motor, with high-resistance rotor windings, is best suited to cranes which handle rough material where no reduced-speed operation is required and where size does not exceed 25 horse power. Under this class would come ice hoists, lumber cranes at not over 50 or 75 ft. per minute, cranes for boxed or baled goods at not over 100 feet per minute, machine shop cranes at not over 15 or 20 feet per minute. The multi-speed motor with squirrel-cage rotor offers many possibilities where reduced-speed operation is required, such as foundry hoists; but this type has not been generally exploited commercially.

There are two important differences between the alternating-current and the direct-current, series-wound motor: (1) Power supply voltage and frequency must be maintained fairly uniform for the alternating-current motor because its maximum starting torque varies as the *square* of the voltage impressed, and inversely as the *square* of the frequency. Voltage has, in practise, no effect on the maximum starting torque of a direct-current series-wound motor because starting torque is a function of current only and even if voltage is abnormally low the controller can be manipulated to give maximum current. It is therefore, necessary to choose a motor whose maximum-minimum[3] starting torque is, at least, twice and for squirrel-cage motors 2.5 or 3 times the torque required for hoisting the maximum load. Consider, for example, a crane where power supply voltage is 90 per cent of rated motor voltage and where static friction is such as to add 25 per cent to hoisting torque at the instant of starting. Then if motor could exert 200 per cent normal torque at starting under normal voltage, it could exert 162 per cent of normal torque under 90 per cent voltage; and it would be called on to exert 125 per cent of normal torque. The difference between 125 per cent and 162 per cent represents the margin, and it is none too great. This margin is not sufficient for squirrel-cage motors because if they stall they are almost sure to burn out the rotor.

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[1] Assume a coefficient of friction between the wheels and the rail of 25 per cent. Then the available draw-bar pull from one-fourth of the wheels will be 25/4 or 6.25 per cent of the weight of the crane. Gravity (or the total weight of the crane) will accelerate the crane at 32.2 ft. per second per second—therefore 6.25 per cent will accelerate it at 0.625 × 32.2 or 2 ft. per second per second. This calculation omits some niceties about rolling friction but they are relatively unimportant.

[2] Three blocks of accelerating resistors produce an average of approximately 72.5 per cent of the peak rate of acceleration; four blocks 78.5 per cent; six blocks 85 per cent; nine blocks 89 per cent; and thirteen blocks 92.5 per cent.

In order to make the same number of trips per day with an a-c. crane as with a d-c. crane, it is frequently necessary to gear the a-c. crane for a higher full-load hoisting-hook speed than would be used with d-c., and this means that the rating of the a-c. motor must be relatively greater than that of the d-c. motor. To explain, let us assume that a round trip consists of hoisting full load 20 feet, lowering it 20 feet, hoisting an empty hook 20 feet and lowering it 20 feet. If a d-c. motor were used and geared for 40 feet per minute full-load hoisting speed, it would hoist in 30 seconds, lower (where lowering speed is 190 per cent hoisting speed) in 16 seconds, hoist in about 15.5 seconds (where 20 per cent hoisting torque corresponds to 195 per cent speed), lower in 20.5 seconds, making a total of 82 seconds. An a-c. motor would have to be geared to hoist full load in about 20.5 $\left(= \frac{82}{4}\right)$ seconds in order to keep up with the d-c. motor because the a-c. motor can never run above its synchronous speed. This means that the a-c. motor would have to be $\frac{30}{20.5}$ (= 1.46) times as large as the d-c. motor for the particular case illustrated. This ratio does not come as high as 1.46 for ordinary practical cases where there is a good deal of creeping speed work in the typical round trip of the crane hoist. However, in order to meet the requirements of an occasional extremely high load, an induction motor may have to be considerably larger than a d-c. motor because a d-c. motor can exert more overload torque.

Use of Permanent Resistance in the Rotor Winding of Slip-Ring Motors. When manual control is used and service is severe and abusive, *a permanent block of resistance* should be wired in series with the slip rings of the motor and should be of such value that the slip at full-load torque on the motor will be about 15 per cent after the controller has been turned to the "full on" position. To accomplish this, the permanent resistance should contain about 10 per cent as many ohms as are required to give 100 per cent slip (or standstill) with full-load torque on the motor. This sounds like wasting power but power is only one of the small considerations in the operation of the crane. The following tabulation of performance values on a certain typical motor shows the advantage of permanent resistance:

Max. stalling* torque in per cent of full-load torque	Stalling amps. in per cent of full load	Per cent slip when motor is delivering full-load torque	Heating when motor is stalled, expressed in per cent of the heating when full-load current is flowing
175	484	5	2340
265	419	10	1750
290	360	15	1300
286	311	20	960
272	278	25	775
255	250	30	625
236	229	35	522
220	208	40	434

*These are maximum-maximum values; not maximum-minimum values.

Operators seem to make a practise of turning these manual controllers on as fast as possible and it is best to plan that the controller will be full on before the motor starts. The above table shows that the most starting torque can be obtained when a resistor is set for 15 per cent slip and that there is a big saving in motor heating at this resistor setting. A careful study of practical operation from all angles will show that with this resistor setting more can be gotten out of the motor than with any other setting, and at less expense in the way of motor and control trouble.

When magnetic control is used, no permanent resistance is necessary because current-limit relays prevent all of the resistance from being short-circuited while the motor is at standstill.

When permanent rotor resistance is used, it is not necessary, in comparing an a-c. motor with a d-c. series motor, to make the full-load hoisting speed for alternating current as much higher than for direct current as was indicated in a foregoing paragraph. In the example used, the full-load lowering speed will be enough above synchronous speed to average up the lower full-load hoisting speed; and, consequently the full-load hoisting speed need be only 129 per cent above full-load d-c. hoisting speed in order to make the round trip in 82 seconds.

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[3] Maximum-minimum starting torque is a term which applies to slip-ring type, wound-rotor induction motors. With the external resistance which is connected to the rotor adjusted for obtaining the maximum starting torque, the currents are so high as to set up a magnetic distortion between the poles of the stator and of the rotor. At some positions of the rotor, this distortion causes the torque to increase and at other positions to decrease. Maximum-maximum starting torque means the torque when rotor is in most favorable position; *Maximum-minimum*, the most unfavorable.

Calculation of Power for Alternating-Current Crane Hoist Motors. Calculate the hoisting horse power as per equation (**1**) and choose a motor whose 30-minute rating is equal to or greater than this value. Where the motor is to be started frequently, calculate starting horse power to start from equation (**13**), choose a motor such that horse power from (**1**) plus horse power from (**13**) does not exceed 150 per cent of the 30-minute rating.

Sometimes, on very rough service, it is advantageous to connect a permanent resistor in the rotor circuit of such value that speed under full load is about 85 per cent of the synchronous speed. When this is done the motor rating is reduced about 10 per cent and, therefore, select the motor so that its 30-minute rating is 110 per cent of the horse power in equation (**1**). Also it is, of course, necessary to gear the motor so that when running at 85 per cent of synchronous speed, the load will be hoisted at rated crane hook speed.

Heating is not usually a limiting feature on open motors when motors are selected as above described except on bucket or similar cranes. When enclosed motors are to be used, or buckets are to be handled, the duty should be referred to the manufacturer for selection of the motor.

Selection of Alternating-Current Bridge-Motion Motors. Wound-rotor motors with slip rings are best suited to this work.

Motors should be open, enclosed or specially insulated to correspond with hoist motor.

Permanent rotor resistance is generally advantageous.

Calculation of Power for A-C. Bridge-Motion Motors. Try a motor such that the horse power to propel, in equation (**23**) does not exceed 75 per cent of the 30-minute rating. The maximum instantaneous torque during starting should not exceed 200 per cent of the full-load rated torque of the motor. Refer to equations (**24**), (**25**) and (**26**); substitute for A a value of torque in pounds at one foot radius which is not over twice full-load rated torque. Then see that a satisfactory rate of acceleration can be attained, cut and try until a suitable size of motor is obtained. On some high-speed cranes, horse power in equation (**23**) may have to be as low as 30 per cent of the 30-minute rating of the motor in order to obtain satisfactory acceleration without overloading the motor.

TABLE I

A KEY TO ASSIST IN THE SELECTION OF ELECTRICAL EQUIPMENT FOR CRANES

- **Electrical Equipment for Cranes**
  - **Motors**
    - **Enclosed or Open, Insulation, Mechanical Strength and Staunchness**
    - **Rating**
    - **Accessibility for Repairs**
    - **A-C.**
      - **Wound Rotor or Squirrel Cage 1-speed or 2-speed**
      - **Voltage**
      - **Frequency**
      - **No. of Phases**
      - **Heating Basis**
        - **15 minute**
        - **30 minute**
        - **60 minute**
      - **Max. Torque**
    - **D-C.**
      - **Max. Torque**
      - **Series or Compound Wound**
      - **Voltage**
      - **Heating Basis**
        - **15 minute**
        - **30 minute**
        - **60 minute**
  - **Control Equipment**
    - **Controller**
      - **Drum**
        - **Straight Reversible**
        - **Dynamic Braking**
        - **No. of points**
        - **Type of handle**
          - **pump**
          - **vertical**
          - **horizontal**
          - **remote lever**
          - **rope-wheel**
          - **spring-return**
      - **Magnetic**
        - **Straight Reversible**
        - **Dynamic Braking**
        - **No. of hand control points**
        - **No. of automatic control points**
        - **Plugging point**
          - **Hand controlled**
          - **Automatic**
        - **Creeping speed point**
        - **Space requirements**
        - **Type of handle on master**
    - **Rheostat**
      - **Heating**
      - **Starting Torque**
      - **Plugging**
      - **Creeping Speed**
    - **Brakes**
      - **Series or Shunt Wound**
      - **Torque Requirements**
      - **Staunchness**
      - **Wearing Qualities**
        - **disk**
        - **shoe**
        - **band**
        - **coasting distance**
  - **Protective Equipment**
    - **Overload**
    - **No-voltage**
    - **Emergency Conditions**
    - **Lock-out on Line Switch**
    - **Individual Motor Switches**
    - **Overwind Protection**
      - **geared**
hook-operated
      - **relay**
main-circuit
      - **reset**
non-reset
      - **inherent**
extra-wire

Selection of Alternating-Currnet Trolley Motors. Use the same type of slip-ring motor as on hoist and bridge.

Choose a motor such that the horsepower in equation (**29**) does not exceed the 30-minute rating of the motor.

On certain small trolleys which do not exceed 250 ft. per minute speed nor 5 h. p., it is possible to use a simple squirrel-cage motor with high-resistance rotor. Such a motor must have a starting torque at least twice the torque required to propel the maximum load as per equation (**29**).

Starting torque in pounds at one foot radius must at least =

$$2 \times \frac{(\text{horse power in (29)}) \times (\text{full load r. p. m.})}{5{,}250}$$

Special heating requirement must be met and special control precautions taken.

Discussion

For discussion of this paper see page 323.

Auxiliary Electrical Equipment for Motor-Operated Cranes

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Review of the Subject.—*This is one of a series of papers on the selection of electrical apparatus for cranes and deals with the brakes, overload protective panels and limit switches. Other papers of the series cover the requirements as to motors and control.*

A magnetic friction brake is needed for every crane hoist, in addition to what may be provided in the way of dynamic braking or mechanical brakes, but its required characteristics are very definitely affected thereby. In selecting a magnetic brake the character of the service must be well understood, and the part that it plays therein, and it must possess an adequate energy dissipating capacity. A definite formula for such selection is given.

The paper discusses the various service requirements and describes the several available types of magnet brakes and their particular fields of application.

Limit switches, while occasionally employed to limit the travel of the trolley or bridge motions of a crane, are universally used to limit the upward travel of the hook block. Hoist limit switches may be geared to the machine or directly operated by the block. The former do not take into account the stretching of cables and require complete readjustment when new cables are installed. Switches operated by the hook block are the surest.

The paper describes the various forms of geared and direct-operated limit switches and points out their relative advantages. Considerations of safety often demand that the operation of the switch not only disconnects the motor but simultaneously closes a dynamic braking circuit for quick stop.

The history is given of the evolution of the modern crane overload protective equipment and devices. Fuses and railway type circuit breakers have been tried, but up-to-date equipment employs overload relays in each motor circuit operating in conjunction with magnetic switches. In the interests of safety it is possible to cut off all power instantly by tripping a switch that causes the magnetic switches to open. Safety locks are provided that permit of locking the entire crane equipment against operation.

The best results are secured by properly inspected time-element overload relays in each motor circuit and a common-return instantaneous relay.

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Review of the Subject. (850 w.)
D-C. Magnetic Friction Brakes. (3400 w.)
A-C. Magnetic Friction Brakes. (900 w.)
Limit Switches. (2850 w.)
D-C. Crane Protective Panels. (1280 w.)
A-C. Crane Protective Panels. (300 w.)

IN addition to motors and controllers, modern cranes also require auxiliary electrical equipment, namely; magnetic friction brakes, overload protective panels and limit switches.

D-C. MAGNETIC FRICTION BRAKES

Every crane hoist requires a magnetic friction brake for the purpose of stopping and holding loads in suspension. If the crane is equipped with dynamic lowering control, a large part of the work of retardation is absorbed electrically, in the dynamic braking resistance. In the case of a crane equipped with a well-adjusted mechanical load brake, the magnetic brake is called upon to absorb only the energy of the rotating armature. In the case of a crane without either dynamic lowering control or mechanical load brake, the magnetic brake is called upon to absorb in friction and dissipate in heat, all of the stored energy in the moving load, gearing and armature. The amount of energy expressed in foot-pounds per minute or per hour which a brake of given type and size may safely dissipate without exceeding a reasonable rise in temperature, is a definite quantity. In selecting a brake for severe duty, the above factors should be considered in connection with the severest probable duty cycle, and a brake should be selected whose energy-dissipating capacity provides some margin of safety above anticipated requirements. A failure to observe this simple precaution in the past has often resulted in serious trouble, especially with brakes of poor heat dissipating capacity.

On a crane without mechanical load brake, the magnetic brake is the sole means of holding a load in suspension. It is, therefore, an important factor in the safe and efficient operation of the crane and care

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must be exercised to select a brake having sufficient torque to hold, and, in case of emergency, to stop the heaviest load which the crane may be called upon to handle. Some manufacturers rate their brakes in horse power, corresponding to the ratings of the motors with which they recommend their brakes to be used. The horse power rating has arisen from the fact that hoist brakes are usually, though not always, mounted on the armature shaft of the hoist motor, and from the fact that the coils for series-wound brakes must be designed on the basis of the motor rating. The torque rating of a brake is, of course, a perfectly definite quantity determined by actual test. The horse power rating is the calculated horse power which the brake would absorb when exerting its rated retarding torque at an assumed speed. The speed is determined by averaging the full-load rated speeds of various makes of hoist motors. As a guide to the approximate size of brake required, the horse power rating is, no doubt, useful but as a basis for the selection of a brake, it may prove positively dangerous. A calculation of the actual torque required to hold the maximum load in suspension should therefore be made and a brake whose torque rating is at least equal to this amount should be selected. This torque can be quickly calculated from the formula:

$$T = \frac{L \times D \times E}{24\,R}$$

where T = Torque in lb-ft.

L = Maximum load in lb.

D = Diameter of winding drum, in inches.

E = Efficiency of gearing.

R = Gear reduction including ropes, between load and the shaft on which the brake is mounted.

Brakes selected in accordance with this plan will, in general have less torque than the motor in connection with which they are used; this is because of the fact that the inefficiency of the gearing is of assistance to the brake whereas it is a handicap to the motor. In order to provide a margin of safety it is therefore customary to select a brake on the basis of motor torque. If the torque rating of the motor is not at hand, or if the brake is to be mounted on some shaft other than the armature shaft the torque can be calculated from the formula:

$$T = \frac{33000 \times \text{h. p.}}{2\,\pi\,N} = \frac{5250\,\text{h. p.}}{N}$$

where T = Torque in lb. ft.

h. p. = Horse power rating of motor

N = Rev. per min. of shaft to which brake is to be attached.

As above stated the hoist brake is usually mounted on the armature shaft of the hoist motor. This is not universally the case, however, and not infrequently brakes are mounted on intermediate shafts. In the case of ladle and hot metal cranes, for example; when dynamic lowering control is used, in view of the great responsibility imposed on the brakes, it is customary for safety reasons, to install brakes both on the armature and on intermediate shafts. Either of these brakes alone should be capable of stopping and holding the load. A brake on an intermediate shaft as compared with a brake on the armature shaft, in order to hold the same load, must develop a greater torque in proportion to the gear reduction.

Intermediate shaft brakes are, not infrequently, too large, or of improper design for the real purpose they are intended to serve. By far the greater part of the stored energy in the system is in the rotating armature. If this energy is absorbed by a brake on the armature shaft, the only parts subjected to stress are the armature shaft and bearings, the motor supports and the brake itself. If this energy is suddenly absorbed by a brake on an intermediate shaft, this shaft, together with its bearings and the gearing, are also subjected to severe stresses. There is always some back lash in the gearing and in consequence, every time the intermediate shaft brake stops the armature, a hammer blow is delivered to the gearing and transmitted to the shafts and bearings. In one direction of rotation this hammer blow is delivered downward and in the other direction, upward, so that the mechanism is continually subjected to alternating stresses of great intensity. On ladle cranes this hammer blow is particularly noticable when hoisting without load, because in this event the motor operates considerably above normal speed. In various installations this effect has been so severe as to break bearing cap bolts, bend shafts, strip pinions and break motor feet. In all such cases, where two brakes are required it is a wise precaution to use a quick acting brake operated by a short stroke magnet, on the armature shaft and a more sluggish brake, operated by a long stroke solenoid on the intermediate shaft. Since this trouble is most likely to occur in hoisting the light hook, it can be almost entirely eliminated by using a dead-end band brake as an intermediate shaft brake, as this type of brake is practically ineffective when the brake wheel rotates toward the anchored end of the band.

The operating coil of a magnetic brake may be series wound, for connection in series with the motor, or shunt wound for direct connection to the power circuit in parallel with the motor, or compound wound, *i. e.*, having both shunt and series windings. Compound wound brakes are rarely used on electric cranes, though their use may be advisable in special applications in connection with compound wound motors, where the load may approach zero. Shunt brakes are sometimes used on standard crane hoists due to the preference of the individual user, but in general shunt brakes constitute an evil to be avoided where possible in crane service. If wound for full voltage their inductive effect makes them sluggish in action and destructive to insulation. If wound for fractional voltage in order to reduce the inductive effect, the additional complication of a fine wire resistor for connection in series with the coil is required. Their use involves the use of additional trolley conductors. If used in connection with a dynamic lowering controller they are a menace to safety because they may be held released by any one of a variety of causes when it is very necessary that they be applied. From the standpoint of safety it is especially desirable to provide some assurance that the brake will automatically set in case of accidental failure of the dynamic braking circuit. This feature can be secured with the shunt brake only by means of the additional complication of a series relay, whose coil is connected in series with the motor precisely as the coil of a series brake would be connected, and whose contacts are connected in series with the shunt brake-control circuit. Shunt brakes must be used where it is desired to provide a drift point, as on bridge and trolley motions and in some special applications. For crane hoist service, however, the series-wound brake has been all but universally adopted, because of its simplicity, reliability, and suitability, for the work. The sole objection raised against the series winding in the past has been that its operating range is too narrow. Following the introduction of dynamic lowering control, it was found that few brakes in service could be depended upon to release at less than 75 per cent of full-load current. Another objection was that series brakes would not hold released to a sufficiently low value of current. However, these objections do not apply to brakes of modern design which will release at 40 per cent and hold released as low as 10 per cent of full-load current or less.

As regards the mechanical arrangement of their friction surfaces, commercial brakes are of three general types, namely, band brakes, shoe brakes and disk brakes.

The most extensively used type for crane hoists is the dead-end band brake. It consists of a flexible sheet steel band, lined with leather, asbestos composition or other friction material, one end of which is firmly anchored by means of a cast or forged ear, riveted to the band. The other end of the band is attached through a suitable adjustable fitting to a lever, which is operated by a long-stroke solenoid. In most designs the weight of the solenoid plunger, assisted perhaps by an adjustable weight on the lever, is made to apply the brake. In other designs the brake is applied by means of a spring. Very considerable improvement has been made in recent years in band brakes as manufactured by the various crane builders by refinement of the structural details and by the adoption of a well-designed single-coil solenoid instead of the old two-coil horse-shoe type operating magnet formerly used. For some purposes, as for example, on an intermediate shaft, the band brake has decided advantages, and for such applications it will, no doubt, long continue to be used. It possesses, however, inherent defects which no amount of refinement in design can eliminate. The most important of these defects is that it is effective in only one direction of rotation. In lowering, the friction between the brake wheel and band tends to wrap the band more tightly around the wheel, and this together with the fact that almost the whole circumference of the wheel is used gives high braking torque. But in the opposite direction the friction between wheel and band simply tends to raise the operating lever, and the retarding torque developed is practically nil. In hoisting the light hook, therefore, an excessive amount of drift is experienced and many accidents, usually unjustly blamed on the failure of limit switches, have resulted in consequence.

Another defect of the band brake is that it is difficult to make it as strong mechanically as other types. The band must possess a degree of flexibility which limits its thickness and therefore its strength, and the ends where the ears are attached are especially apt to fail. Every one with steel mill experience has seen these bands fail, perhaps with disastrous results. In actual practise the band nearly always drags more or less, imposing a friction load which detracts from efficiency. The long-stroke solenoid is sluggish in action as compared with a short-stroke electromagnet, so that in hoisting a heavy load, when the controller is brought to the off position the load may start to drop before the brake sets. When somewhat out of adjustment and operating through an excessively long stroke the hammer blow developed when the plunger drops, gives for an instant an excessive braking torque which throws severe stresses on brake band and gearing, sometimes resulting in damage to both.

These various defects of the band brake are rapidly forcing the more general use of shoe and disk brakes. The shoe brake consists of a brake wheel and a pair of shoes lined with friction material, and operated through the proper mechanism by either a short-stroke electromagnet of the clapper type or a solenoid. When a clapper type magnet is used, the brake is set by means of a spring. When a solenoid is used, the weight of the plunger is usually assisted by a spring. The only serious defect of the shoe brake is that it is practically impossible to use much more than one-half of the circumference of the brake wheel as a bearing for the shoes. Therefore, if the pressure per square inch is kept down to a value which will allow long life to the friction material, a considerably larger brake of the shoe type than of the band type will be required for the same torque. As compared with the band brake, the shoe brake has the following definite advantages; it gives the same braking torque in either direction of rotation; it is a stronger mechanical structure, when operated by a short stroke magnet it is much quicker in action and yet has less instantaneous excessive braking; it is easy to keep it so adjusted that the brake shoes do not drag.

The disk brake consists of a set of one or more rotating disks, feather keyed to a hub which is in turn keyed to the shaft to be retarded and a set of stationary disks feather keyed to the frame of the brake. Either the rotating or stationary disks may be faced with friction material. The armature plate of the short-stroke operating magnet is moved forward by a spring, pressing the friction plates together when the brake is applied. When the magnet is energized the spring is compressed, and the friction plates float apart. The positive advantages of the disk type construction are that it gives equal braking torque in either direction of rotation; it provides plenty of friction surface and, therefore, gives relatively high torque in a relatively small and compact structure; because its friction surfaces are enclosed it gives a very constant torque, regardless of weather, splashing, oil or other untoward conditions. Its positive disadvantages are that on account of its compact structure it will dissipate relatively little heat; on account of the necessarily small bearing of rotating and stationary disks on the feather keys, the wear in both keys and keyways is excessive in severe service; the operating magnet simply relieves the pressure on the disks, when the brake is released and does not positively disengage the disks. This aggravates the trouble from heating; if it is desired to replace the armature or other shaft to which the brake is attached, it is necessary to entirely remove the brake.

To sum up, then, each type of brake has its advantages and its particular applications. The band brake should be used where a holding brake is desired. Its excellent torque characteristic in one direction of rotation is a positive advantage in such service. The shoe brake is a general service brake and should be used for all severe duty applications. The disk brake is also a general service brake which will give excellent satisfaction in light duty applications. Its use is frequently dictated by space limitations.

All of the three types of brakes above described are subject to the same objection, namely, that their torque is either all on or all off; in other words, they do not permit any graduation of braking torque. For most applications, this is not a grave disadvantage. Where dynamic braking control is used, the load is retarded by a nicely graduated braking torque and the fixed torque of the magnetic brake is of no consequence. In many cases where no great nicety of control is required, even without dynamic braking control, no difficulty is experienced if the brake is reasonably well proportioned with reference to the motor and the load. In special applications, however, the fixed torque characteristics of the ordinary brake is a very serious disadvantage. For example, take the case of the bridge motion of a gantry crane which it is desired to hold against any probable wind pressure. In such a case, the torque required of the brake bears no definite necessary relation to the motor torque. If a brake sufficiently powerful for safety in emergency is used, entirely too severe braking for ordinary service application will result. The swinging motion of a jib crane or a hammer head crane presents a similar difficulty. A too severe application of the brake produces objectionable and even dangerous swinging of the load, and, sets up excessive stresses in the structure. Various attempts have been made to properly take care of these difficulties. One method is to use a dash pot to secure gradual application of the brake. This is open to the objection that the brake must always be gradually applied, even in emergency when it may be necessary to apply it instantly in order to avert a wreck. A more satisfactory solution is the use of a multiple solenoid or multiple magnet brake.

The multiple solenoid brake consists of practically two brakes in one, one solenoid being arranged to release the greater part of the total braking torque and the other solenoid arranged to release a smaller part of the total torque. Both solenoids may be shunt wound or one may be shunt and one may be series wound, depending upon the convenience of control. There are various methods of controlling these brakes depending upon the particular application in which they are used. Both magnets may be released at once when the controller is thrown to the off position, and the action of the more powerful one delayed by a dash pot so that the smaller brake does practically all of the work of bringing the structure to rest, and the more powerful brake is then effective as a holding brake. A second method is to release the more powerful brake on the first point of the controller and the less powerful on the second point. This scheme permits the operator to secure full braking torque in emergency. A third method consists in releasing the large solenoid on the first point, the small solenoid on the second point and in providing a drift or coasting point on the third control notch at which point neither brake nor power is applied. Many applications where a drift point is very desirable will occur to the reader. It must be kept in mind, however, that with this scheme both solenoids must be shunt wound, involving at least two additional trolley conductors, and this feature may be very objectionable.

The second scheme mentioned above has a special application in connection with dynamic lowering hoist controllers which deserve particular mention. A defect of the standard dynamic lowering systems of control is that it is difficult or impossible to secure creeping speeds in lowering heavy loads. If reference is had to a dynamic braking speed torque curve (See paper by James A. Jackson, *General Electric Review*, June 1917, page 462) it will be noted that for the motor to develop a dynamic braking torque equal to full load torque it is necessary that the armature rotate at about

35 per cent of full load hoisting speed. In other words, it is difficult to secure more than 65 per cent speed reduction in lowering a heavy load, without dangerously overloading the field windings, whereas 90 per cent speed reduction is not infrequently required. This defect of dynamic lowering control is due to the fact that the retarding torque is proportional to the product of the currents in field and armature. The maximum safe field current must be assumed to be full-load current. In order to develop full-load torque the armature must therefore generate full-load current and it will accelerate to the speed necessary to enable it to generate sufficient voltage to force full-load current through the resistance of the dynamic loop. The minimum safe value of resistance in the dynamic loop is also quite definitely determined by considerations apart from speed control. It is evident, therefor, that the only safe way to reduce the minimum lowering speed with heavy loads is to relieve the motor of some of the overhauling torque. This can be very effectively accomplished by means of the multiple solenoid brake. If the smaller brake remains applied, as outlined in the second scheme of operation mentioned above, on the first point of the controller, excellent speed regulation may be secured, even with the heaviest loads the crane may be called upon to handle.

A-C. MAGNETIC FRICTION BRAKES

Alternating-current brakes are either of the band or shoe type operated either by solenoids or clapper type magnets, or by small torque motors. In general, what has been said above with reference to d-c. brakes applies with equal force to a-c. brakes. It is to be constantly kept in mind, however, that alternating current cranes are rarely found in exceedingly severe duty, so that defects which may be quite serious in d-c. equipment may be unimportant in similar a-c. equipment. Furthermore, on account of the synchronous speed characteristics of the wound-rotor induction motor, the brake is relieved of all danger of excessive stresses and wear because of the excessive speeds often encountered in severe duty d-c. equipment. On the other hand there is no system of dynamic lowering control for a-c. hoists and many a-c. cranes are installed without mechanical load brakes. In consequence, a-c. brakes must usually absorb all of the energy of stopping the load, and usually they constitute the sole means of holding a load in suspension. A strong and reliable brake is therefore essential.

The constant speed characteristic of the wound-rotor induction motor makes a mechanical brake unnecessary for limiting the lowering speed of an overhauling load. The motor is simply accelerated to synchronous speed and above this speed true regenerative braking is secured and power is returned to the line. On the other hand, if no mechanical brake is used, it is impossible to secure a nice speed regulation in lowering an overhauling load, since no system of control for a-c. motors comparable to dynamic braking control for d-c. motors has been designed. This has led to the development of the solenoid load brake, which eliminates many of the inherent disadvantages of the mechanical load brake and secures effectively the desired accuracy of speed control.

The solenoid load brake consists of a single brake wheel and a single pair of brake shoes mounted in an appropriate frame and operated by two solenoids. One solenoid which is connected in the primary circuit is arranged to entirely release the brake when energized. The second solenoid is connected across one phase of the secondary or rotor winding with some variable resistance in series with it. Since the voltage generated by the secondary of an induction motor varies directly as the slip and since the pull of the solenoid can be made to vary almost exactly with the voltage across its coil, the pull can be made almost exactly proportional to the slip or inversely proportional to the speed. This solenoid is of course arranged so that the pressure on the brake shoes is relieved by the pull of the solenoid, so that when the pull is a maximum, that is when the rotor is at standstill, the braking torque is almost entirely relieved, whereas at high speeds, where the slip approaches zero approximately full torque is developed. The braking torque at low speeds can be increased by increasing the variable resistor in series with the solenoid coil. This resistor is controlled by the contacts of the hoist controller, so that operation very similar to that of a dynamic lowering d-c. controller is secured. In hoisting, the solenoid in the primary circuit is energized and this entirely releases the brake so that there is no braking friction in hoisting. On the first three or four points lowering only the solenoid in the secondary circuit is energized, so that on these points accurate speed control is secured by means of the solenoid load brake. On higher speeds the solenoid in the primary circuit is energized and the braking torque of the solenoid load brake is entirely relieved and the load may be lowered at high speeds by pure regenerative braking. The brake is therefore relieved of wear except when operating at low speeds and in slowing down from high speed to low speed. As compared with a mechanical load brake, very much less wear due to friction is encountered and much less frequent adjustment is therefore necessary. The solenoid load brake will give as good results on creeping speeds when lowering loads as the mechanical load brake, assuming equivalent adjustment; especially accurate control is secured in lowering a heavy load a very short distance, usually called "jogging".

In conclusion it seems advisable to emphasize the importance of substantial and capable braking equipment on electric cranes. A good dependable hoist brake is perhaps more important from the standpoint of safety than any other item of electrical equipment on a crane. This subject deserves more consideration than has hitherto, in general, been given to it. The brake is an insignificant item of cost in the total price of a crane, so that even a cheap crane could well afford a good brake, but it has been very largely overlooked by the purchasers of cranes and many unsatisfactory and even unsafe brakes are in daily use. If this paper serves in any degree to direct more careful consideration to the matter of magnetic brakes for cranes, the author's object will have been accomplished.

LIMIT SWITCHES

The function of limit switches as applied to electric cranes is to limit the travel of either hoist, trolley or bridge motion in either one or both directions. Their most common use is to limit the upward travel of the hook block.

Hoist limit switches are of two general types; first, geared; second, direct-operated by the hook block. Geared limit switches consist of a contact mechanism connected to the drum shaft through some such reduction gear as a traveling nut, worm and gear or interrupted gear. This contact mechanism is usually designed to handle a control circuit only, so that in addition to it, a magnetic switch or circuit breaker to break the motor circuit is required. Direct-operated limit switches are of either the control circuit or the main circuit type. The control circuit type consists of a simple normally closed contact opened directly by the hook block, and a magnetic switch. The main circuit type consists of a more substantial contact mechanism, capable of handling the motor current, operated directly by the hook block. It may simply open the motor circuit, or it may in addition provide some form of dynamic braking to secure a quick stop.

As mentioned above, geared limit switches are supplied with either a magnetic switch or a circuit breaker, of the shunt trip type, to open the motor circuit. A sharp distinction must be drawn between these two types. If a shunt trip circuit breaker is used, the geared contact mechanism must have normally open contacts. When the hook approaches the limit of travel, the contacts are closed, the shunt trip coil energized and the circuit breaker thus opened. It is therefore dependent upon the integrity of its circuits for its operation. Its contacts may be out of commission, a shoe may fail to make contact with a trolley bar, or a connection may be loose and the limit switch is inoperative. The important point is that it gives no previous warning or indication of its condition and the hoist may continue to operate until the hook block over-travels and an accident results.

The device with normally closed contacts and a magnetic switch, on the other hand, is normally safe. The magnetic switch will be opened by any failure of the limit switch circuit and the hoist cannot be operated until the fault is repaired. The magnetic switch may of course be held closed by a grounded circuit, independent of the action of the limit switch contacts and thus cause a wreck. However, the danger of grounds is small as compared with the many possibilities of open circuits and the closed circuit device is therefore a much safer and more dependable limit switch than the open-circuit device.

The magnetic switch may be mounted either upon the trolley or in the operator's cab. There is some advantage in mounting upon the trolley. It may not be so easily tampered with and the control wiring runs only a short distance so that there is less danger of grounding. If the magnetic switch is mounted in the cab, it is a wise precaution to put it in a locked enclosing case, so that it cannot be tampered with by unauthorized persons.

The method of resetting the limit switch is important. Any method, such as the use of a push button, which will permit further hoisting after the limit switch has operated, is to be condemned. A control circuit wire, energized by a finger in the hoist controller is often used, and is an excellent method if the necessary contact finger in the controller is available. This connection simply short-circuits the limit switch contacts when the controller is thrown to the lowering position, and the limit switch is reset automatically when the hook has lowered a short distance. A still better method is to connect the main contacts of the magnetic switch in a part of the circuit which is used only in hoisting. It is possible with most reversing controllers and with all dynamic lowering controllers, to make this connection and with this arrangement no control circuit connections whatever are required for reset. It is needless to say that careful and constant inspection is necessary if such limit switches are to be depended upon. The mechanical parts of the contact mechanism require especially close inspection. A flexible coupling of some sort is required between the drum shaft and the operating shaft of the limit switch, because of difficulty in securing accurate alinement. The couplings in general use at the present time are of poor design and are sure to give trouble unless frequently inspected and replaced when necessary. The bearings of the operating shaft require thorough lubrication. Accidents occur because these bearings become so badly worn that the reduction gears fail to mesh and the contact drum is therefore not driven.

All geared limit switches are open to the very serious objections that they take no account of the stretch of the cables and require complete readjustment whenever new cables are installed. If the limit switch is set with a new cable, to stop the hook travel at the proper level, it quickly develops as the cables stretch that it is impossible to hoist to the desired height, and readjustment is necessary. The direct-operated control circuit type limit switch avoids this difficulty and in addition has the advantage of being a very simple and strong device, and of being subjected to very little wear, because it operates only when the hook reaches the limit of travel. The contact mechanism hangs under the trolley and at least a superficial inspection of it can be made from the floor. For cranes equipped with shoe or disk brakes, giving full braking torque in the hoisting direction and where from twelve to eighteen inches of variable drift may be permitted, this type of limit switch makes very satisfactory equipment. It provides a very considerable degree of protection at very little expense. It is important to remember, however, that a good disk or shoe type brake is very necessary for the reliable operation of such a limit switch.

The extensive use of band brakes, which provide almost no retarding torque in the hoisting direction, and the close limits within which many crane hoists have to work, has lead to the development of direct-operated main circuit limit switches, which in addition to opening the motor circuit, establish dynamic braking connections, in order to secure a quick and accurate stop.

The first devices of this kind were developed in the steel industry which is still their principal field of application. The first development, known as the 2 by 4 limit switch consisted simply of two pieces of 2-in. by 4-in. lumber from two to four feet long connected together at one end by a common door hinge and having mounted upon them at their other ends a pair of carbon blocks. This device is swung under the trolley with its contacts normally open, in such position that the contacts will be closed by the hook block lifting the lower two by four as the hook approaches its limit of travel. The electrical contacts are connected to short-circuit the armature when closed. The tremendous rush of current in the field and the heavy circulating current in the armature brings the hook almost instantly to rest. At the same time the circuit is supposedly opened by the blowing of the circuit breaker in the cab. To reset this limit switch it is necessary to pry the 2 by 4's apart while the hook block is lowered out of the limit.

This limit switch which is extremely effective in securing a quick and accurate stop, is cheap, strong and easily inspected. But it is evident that the operation of such a limit switch must be considered a serious emergency. In addition to the time and trouble required for resetting, the damage accruing to the motor is a serious matter. A flash-over almost inevitably results and after a very few operations of the limit switch the motor must be sent to the repair shop. Furthermore, under certain conditions of operation it is ineffective. If the hoist controller is not in the full on position, that is, if the current in the field circuit is limited by a portion of the starting resistance, the armature will be slowed down but will not be brought to a stop unless the circuit breaker happens to blow. If power fails, or if the hoist controller is brought to the off position at the instant the hook strikes the limit, the switch is absolutely ineffective. This latter contingency is more than probable since an operator will instinctively throw his controller to the off position when he sees the hook approaching the danger point. Very frequent failure of this type of switch may therefore be anticipated and has actually resulted in practise.

This device scarcely deserves consideration here except for the fact that it has served to direct the attention of control manufacturers to the need for a limit switch designed to give quick and accurate stops. The first development along this line consisted of a switch built along the lines of a drum controller, arranged to break the line connections and reconnect the motor with armature reversed as a series generator with a current-limiting resistor in circuit. By adjusting the resistor, practically any degree of braking and therefore any quickness of stop desired may be secured. In the interest of reliability it is wise to use a resistor of non-breakable material, since it must be mounted upon the trolley and since the quick dynamic braking stop depends upon the integrity of this resistor. This type of stop is widely used and gives excellent satisfaction. The objection to it is that it must be reset by hand, and for this purpose a reset rope is provided. The trolley must be run back toward the operator's cab so that the operator can reach the rope which results in some inconvenience and delay. To escape this objection, self-resetting, direct-operated switches have been designed. These switches secure dynamic braking in the manner described above, but in addition, close contacts which establish connections for lowering when the controller is thrown to the lowering position. The hook is lowered at low speed with a shunt around the motor until the hook is out of the danger zone, when the limit switch is automatically reset by a weight and the hook may be lowered at full speed.

If it is necessary to secure a very quick stop, say within four to six inches of drift with the light hook, the dynamic braking resistance will have to be so small and the braking current so heavy, even with this type of limit switch, that the commutator will be pitted and flash-overs may result. If the resistance is so proportioned as to allow a dynamic braking current equivalent to full-load current, only full-load braking torque is generated initially, before the motor begins to slow down and the average braking torque will be only about half full-load torque. Since the dynamic braking torque is proportional to the square of the current it is evident that about 150 per cent full-load current must flow on the dynamic braking peak in order to secure even as quick a stop as would be secured with a full-torque magnetic friction brake without the assistance of dynamic braking. It is evident, therefore, that by far the best results will be secured by using a good brake of the shoe type in conjunction with the dynamic braking limit switch where very accurate stops are required. Thus with a dynamic braking peak of 200 per cent and a full-torque magnetic brake, an armature rotating at twice full-load speed should be brought to reset in about two-thirds of a second. If the hook speed is fifty-feet per minute, the drift will be about six inches.

As may be seen from the foregoing, the whole matter of hoist limit switches is in a rather chaotic condition at the present time. There is no conclusive and definite opinion among operating men as to what constitutes a good limit switch. Some operating engineers take the position that no limit switch is thoroughly dependable and that a limit switch which is not dependable is worse than none at all. Some maintain that the operator should not be permitted to depend upon the limit switch and that he should be put to some trouble to reset it, so that he will avoid using it if possible. Others maintain that such loss of time in resetting is not permissible and that automatic reset is positively necessary. Still others consider the matter of slight importance and accept without question anything in the way of a limit switch which the crane builder may provide. New cranes are being installed every week with every type of limit switch mentioned herein, from the open-circuit geared type, which the author frankly believes to be worse than no limit switch at all, to the most elaborate form of dynamic-braking direct-operated, self-resetting type. There is literally no standard specification for limit switches either as regards structure, as regards functions or as regards what they shall accomplish. In the hope, therefore, of assisting in the formation of a definite sentiment on this subject, the author ventures to submit his own opinions as follow:

Hoist limit switches should be operated directly by the hook block and should preferably open the motor circuit without the intervention of a magnetic switch or circuit breaker. On cranes equipped with disk or shoe type magnetic brakes and on which the drifting space is ample, a limit switch which merely opens the circuit is sufficient. On cranes equipped with band brakes and on cranes operating with very small head room dynamic braking limit switches should be used. The head room used by upward drift of the hook when retarded from three times rated speed by a full-torque brake, amounts to about three feet when full load speed is 60 feet per minute, 18 inches for 30 feet per minute, and so on in proportion. The above applies when high-speed motors of the so-called crane type are used; about one-half the drift would occur with the lower-speed so-called mill type motors. Hoist limit switches should always be considered emergency devices. Their use for service stops should be discouraged. The most obvious method of discouraging their continual use is to put the operator to some inconvenience in order to reset. It should not be necessary, however, for the operator to climb upon his trolley or endanger himself in any way, and it should not be possible for him to reset and continue to hoist either by accident or intention. It should be effective regardless of power failure or the position of the controller at the instant of operation. The operating mechanism should be positive, and no dependence should be placed upon springs or other mechanism exerting a definitely limited operating force. Direct operation through push rods or steel cable is preferable. In the limit switch itself, simplicity and strength are of the utmost importance. In the purchase, installation, operation and upkeep of a limit switch it should be constantly kept in mind that it is primarily a safety device upon which the safety of human life may very frequently depend and that therefore the best is none too good.

The foregoing has all been with reference to limit switches for limiting the upward travel of the hook. Where a lower as well as an upper limit is required, commercial types of direct-operated stops are not easily applied. In such cases it is customary to use two complete geared limit switches, or a single geared mechanism, such as is used with elevators, containing two adjustable sets of contacts working in conjunction with magnetic switches.

Limit switches are sometimes required to prevent the collision of trolleys on double trolley cranes, or of the cranes themselves when several cranes are mounted upon one runway. Direct-operated dynamic-braking switches have been applied to some extent for this purpose. Another method is to equip the trolley or bridge motors with magnetic friction brakes, normally held released by shunt-wound magnet coils and automatically applied by means of a direct-operated contact device when the machines come into dangerous proximity to one another. This problem, however, does not often arise.

For alternating-current cranes, the same remarks which have been made regarding direct-current cranes apply insofar as they refer to the method of mounting, of operating and of opening circuits. Dynamic braking cannot be secured with an alternating current motor, independent of an outside source of power and the remarks made regarding the use of dynamic braking limit switches therefore do not apply to alternating-current cranes. Fortunately the a-c. motor does not run at a very much higher speed on no-load than it does on full load. The amount of drift is therefore quite constant independent of the load on the hook, so that, if reliable brakes are used, quite accurate stopping may be secured with direct-operated limit switches which merely open the circuit.

DIRECT-CURRENT CRANE PROTECTIVE PANELS

It has always been the practise to equip electric cranes with some form of protective panel, mounted in the operator's cab, provided with a service knife switch for disconnecting all of the circuits on the crane from the power lines and with some form of individual overload protection for each motor. A vast improvement has been made in recent years in the character of this equipment as offered by the electrical manufacturers, but cranes are still sometimes provided with protective panels of the crude original type. We will, therefore, take up the various types of crane protective panels in the order of their development since even the crudest type is still sometimes furnished on an otherwise modern crane.

The simplest form of crane protective panel consists of a main knife switch with open link fuses and a link fuse in one side of each motor circuit. The unsatisfactory and unsafe character of this equipment scarcely requires comment. The first step in advance from this type is, naturally the use of enclosed fuses instead of link fuses and in this form the fused crane protective panel is very widely used. The protection furnished by this equipment, however, is not very great, and in the case of severe duty cranes is, in fact almost negligible. On severe service cranes heavy momentary over loads are a necessary incident of normal operation. It is, therefore, necessary to use fuses of such large capacity that they afford no protection to the motor or mechanical equipment against continuous overload. For example, a bearing cap in the bridge drive may be pulled up too tight, imposing an overload of 25 or 50 per cent on the bridge motor. In such an event, a fuse, as ordinarily used, in the bridge motor circuit would be unlikely to afford any protection to either the motor or bearing. The panel may be properly fused when new, but it is unlikely to remain so very long. Proper replace fuses often are not at hand when required, and in this case a piece of copper wire is commonly used as a re-fill, which may be replaced at some distant date or not at all. If rigid inspection is enforced and an attempt is made to use fuses of the proper capacity to afford real protection, the replacement of enclosed fuses on a severe duty crane is a considerable item of expense. These disadvantages all indicate the fundamental unsuitableness of fuses for the protection of crane motors and have to some extent forced the adoption of circuit breakers.

Railway type circuit breakers have been used to some extent in this service, in various combinations, and it is rather remarkable that their use is not more general. They constitute a strong and simple protective equipment at comparatively small expense. They avoid the two most important defects of fuse protection, because they may be quickly reset at no expense. The sole serious objection to them is that they must be set too high to give any protection against continuous overloads.

The modern crane protective panel, now almost universally used in the steel industry, has been developed with the view of providing safety protection for the operating force as well as electrical and mechanical protection for the crane. In the interest of safety in emergency it is often desirable that the operator be able to cut off power instantly. This is best accomplished by push button operation of the circuit breakers with the push button mounted within easy reach of the operator. In the interest of safety of workmen engaged in routine inspection and repairs it is desirable to provide means for making it impossible to accidently start any motion of the crane. This is accomplished by providing a safety plug, which the workman takes out of the panel and carries with him in his pocket, while he is on the crane and the absence of which from the panel makes it impossible to close the main circuit breakers; or by providing a safety lock clip on the service knife switch by means of which the workman locks the knife switch in the open position with a safety padlock, the key of which he carries in his pocket. Overload protection is secured by means of overload relays in each motor circuit operating in conjunction with magnetic switches. Various combinations of overload relays are used, depending upon the preference of the user. However, a quite definite standard specification seems to be forming and the type now most generally used has one overload relay in one side of each motor circuit and one common or totalizing relay in the opposite side of the main circuit.

On account of the ease and quickness with which this magnetic contactor type of circuit breaker can be reset it is possible to set the overload relays so that they will trip at a comparatively small overload without interfering too greatly with normal operation. Such a protective panel, therefore, affords some protection against continuous overloads. A much greater degree of protection is secured by the use of inverse time element overload relays. It has become quite common practise to use one inverse time element overload relay in each motor circuit to protect the individual motors against continuous overloads and an instantaneous trip relay in the common or return side of the circuit. This arrangement undoubtedly provides the ideal protection if the equipment is kept in good operating condition, but with the care which such equipment commonly receives in service, it is not wise to put too much reliance upon it. The inverse time element characteristic is usually secured by means of an oil dashpot and its accurate operation depends upon the use of a specific oil having very definite physical characteristics. If some other oil is used the inverse time element feature becomes unreliable or useless. The use of oil moreover tends to assist in the accumulation of dust and grit on the apparatus, which tends to destroy not only the reliability of the inverse time element feature but in addition may retard or actually prevent the operation of the relay itself. The author does not wish to be understood as condemning panels which make use of inverse time element overload relays. If carefully inspected and kept up they certainly provide a very valuable protection, which can be secured in no other way. Our desire is to emphasize the necessity for this inspection with existing types of equipment, and further to present the problem of securing the time element feature in some more simple and more reliable way.

The selection of the proper sizes of knife switches and magnetic contactors for crane protective panels is of importance. In general it is impossible to calculate with any degree of accuracy the current which, flowing continuously would produce a heating effect equivalent to the varying loads on the several motions. Each motor is operated intermittently but usually not in any definite cycle. Two or even three motions may be operated at the same time. There are so many variables depending upon the infinite variations of actual service that an attempt to standardize at first seems hopeless. However an examination of heating curves on a standard line of 30-min. rated enclosed crane motors shows that they can work at their rated load less than 20 per cent of the total time; also that they will, with rare exceptions, and that on small sizes only, carry no more than 35 per cent of their rated load continuously. This indicates that no matter how the currents flowing to the several motors on the crane are superimposed on one another, the root-mean-square value of the current passing through the main knife switch and magnetic contactors, could not exceed 35 per cent of the sum of the rated currents of the several motors, provided the motors were of such capacity as never to be overheated themselves.

Actual experience, quite independent of the consideration of motor ratings, has evolved a standard which is now in general use. The rule is to use magnetic contactors and main line knife switches whose continuous rating is equal to 50 per cent of the sum of the half-hour current ratings of the several motors on the crane. This rule may be used with confidence in making specifications for crane protective panels for all general purpose cranes having three or more motors. Discretion must of course be used in connection with unusual cases. The arc rupturing capacity of the magnetic contactors, should not be less than three times the normal current of the largest motor on the crane.

ALTERNATING-CURRENT CRANE PROTECTIVE PANELS

The problem of overload protection for alternating-current cranes is entirely different from that presented by direct-current cranes. In the first place, an alternating-current motor does not need to be protected against exerting too great a torque instantly. It will inherently stall at somewhere between 2½ and 3½ times full load torque, whereas with a d-c. crane motor, torque can be developed to the destruction of motor or gearing unless a protective device of some sort intervenes. An overload device is therefore required in connection with an a-c. crane motor almost solely for the electrical protection of the motor, and not as on d-c. cranes for the mechanical protection of the motor and gearing. In the second place, in an a-c. crane motor greater starting peaks of current are required for the same motor output than in a d-c. motor, so that any overload device which is unable to differentiate between excessive peaks and continuous overloads of lesser magnitude, is even less useful for the protection of an a-c. crane motor than for a similar d-c. motor. In addition to these considerations, the use of fuses is especially to be condemned in connection with a-c. crane motors because of the danger of single phasing, which might easily result in serious accident.

The satisfactory protection of an a-c. crane therefore depends upon the use of reliable inverse time element overload relays. These relays are usually of the duplex type, that is, with two coils operating upon one control contact. One such relay should be used in the primary circuit to each two- or three-phase motor and in addition, a totalizing relay, connected in series with the wire or wires not protected by the individual motor relays may be used if desired.

Discussion

For discussion of this paper see page 323.

Electric Crane Controllers

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***Review of the Subject.**—Other papers in the series on electrical apparatus for cranes deal with the requirements as to motors and auxiliary equipment; the latter comprising brakes, overload protective panels and limit switches. This paper on controllers reviews its subject in a general way, without going into any details of the devices employed, presenting a clear view of the fundamental considerations involved.*

The controlling apparatus of an electric crane is responsible for the prompt and proper accelerating of the several motions; their speed control; the safeguarding of the motors from abuse; the convenience and economy of operation; and the elimination of many dangers due to carelessness. The author touches indirectly on these points but concerns himself chiefly with the character of the controllers best suited to the bridge, trolley and hoist under various conditions.

The paper deals fully with the problems concerning the selection of ohmic values for the resistors and also covers very completely the connection arrangements and resistance values involved in the dynamic braking control of lowering loads.

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INTRODUCTION

THE controlling apparatus of an electric crane is to the machine on which it is used as the nervous system is to the human body.

The best designed and most scientifically selected motors or brakes would be practically useless without the proper means for controlling the energy that must be applied to them to do the work intended. Furthermore, the dissipation of the energy stored in the crane bridge or trolley during acceleration, or in the loads that have been lifted by the hoist, in order to bring these structures to rest, or to lower the loads, is of as great importance as the application of energy in the first place. Friction devices can be used for this purpose, but the resulting wear on the friction surfaces requires frequent replacements and adjustments, particularly on hoists. It has been stated by some one that the energy given up in lowering 20 tons through 50 feet will generate sufficient heat to raise the temperature of 10 lb. of iron 1000 deg. fahr.

It is well-known that friction brakes for lowering were long a source of trouble on crane hoists. Due to the ability of a direct-current motor to convert mechanical energy into electrical energy, as well as to perform the primary function of translating electrical energy into mechanical energy, the motor, in many cases, can be used for retarding also and thus relieve or replace the friction brake for this purpose. The energy is not all radiated from the motor itself, but mostly from resistors connected in the motor circuit. In the resistors the electrical energy is changed into energy in the form of heat, and is transmitted to the air. It is easy to design and proportion resistors to do this without any great depreciation, and the energy can be radiated into the air wherever it is most convenient. There is some additional heating in the motor when used for both applying power and retarding, but on crane work this is not enough to exceed the safe limits of a motor that is large enough to meet the other requirements of starting torque and commutating ability. However, on hard worked cranes and hoists, performing a definite cycle of operations, such as the hoist of an ore bridge, or special cases where loads are hoisted and lowered through long distances, the heating due to the dynamic braking current should be taken into account in figuring the size of motor required. On account of the twofold function of the motor, we will consider the question of control in two parts. The first will relate to controllers which are used only where energy is applied to the motor to accelerate and move a load, and which we will call *plain controllers*, and the second to those in which, in addition to accelerating and moving a load, the motor is also used to retard and stop a moving load, and these we will call *controllers with dynamic braking*.

APPLICATION OF PLAIN CONTROLLERS

Plain controllers are used for either direct or alternating-current motors, and on cranes are usually of the reversing type. The bridge and trolley motions of cranes require controllers of this description. On hoist motions of cranes, with friction brakes for lowering, either reversing or nonreversing controllers will be required, depending on the design of the brake. The first crane hoists were doubtless made with hand-operated brakes for lowering, and if the load on the hook would overhaul the motor, the speed in lowering was regulated by hand or foot, no power being required in the motor during lowering. Mechanical load brakes have been used for a number of years for hoists which are so designed that if the speed of the lowering load exceeds that of the motor, friction is applied to retard it. This form of brake requires the use of a plain reversing controller, but on account of the advantages of controllers with dynamic braking on hoists, it is now used only in special cases.

Direct-current motors are most commonly used for cranes, for the reason that better starting conditions and better speed control can be obtained by their use.

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Alternating-current motors, usually of the slip-ring type, must sometimes be used because the power supply available is alternating current, and the expense of converting it to direct current may not be warranted. On direct-current cranes the motors for all motions are usually series-wound on account of their strong construction, high starting torque and their characteristic feature of adjusting their speed to the load. Due to friction of gearing, bearings, ropes, etc., there is always sufficient load on the motor to prevent over-speeding, except on overhauling loads on hoists, for which a system of control using a series motor will be described later. Shunt field windings are seldom used, except for bridge or trolley motions where dynamic braking is sometimes required.

Plain controllers for bridge, trolley or hoist motions may be either of the manual or magnetic contactor type. In general, it may be stated that for small motors, or large motors not frequently operated, manual controllers are satisfactory. For motors that are operated very frequently, or for motors of large sizes, magnetic controllers are more desirable for the reason that the small and easily operated master switch relieves the operator of considerable manual labor, and enables him to do more work. Magnetic contactor controllers can also be provided with current limit acceleration, and the motors, as well as the machinery, can thus be protected from damage due to a careless or too ambitious operator attempting to accelerate the motor too rapidly.

The functions of a controller in connecting a motor to the line for operation in either direction are well understood. The controller, either manual or magnetic, should be designed to open or close the circuits with the least amount of wear, and ample provision for taking care of the arc should be made. The wearing parts should be easily accessible for renewals.

On magnetic contactor controllers it is important to have at least two independently operated contacts for opening the motor circuit, so that failure to stop, due to sticking of contactors, will be minimized. This is particularly necessary on hoists, and the addition of a hoist limit switch for positively opening the motor circuit when the hook block reaches the upper limit of travel is desirable from the standpoint of safety to workmen below the crane. Failure to stop the hoist motor often results in breaking the hoisting cables when the hook block strikes the drum or a cross member on the trolley, and the hook block falls to the ground. Even with no load on the hook, men have been killed from this cause.

CALCULATION OF RESISTOR OHMIC VALUES

An important point in connection with controllers for cranes is the ohmic value of the resistors used with them. It is well-known that a direct-current motor can not be connected directly across the usual source of power until it has developed a suitable counter e. m. f. Several factors determine the value of the resistor in addition to the requirements for accelerating the motor, gearing and load:

(1) The starting torque required.

(2) The speed control desired.

(3) The protection on reversing controllers when "plugging," which is reversing the current in the armature while running in order to make a quick stop.

On bridge motions the torque, and consequently the current, required to start the motor is usually close to the full-load torque of the motor. On most cranes the ratio of hook load to the total weight of the crane is small, so that the load on the hook does not greatly affect the starting current required. The fact that the load is suspended by ropes also reduces the effect of the hook load in starting. On account of uneveness in the crane runway, even greater current may be required at times. If the resistor for a bridge controller allows less than full-load current to flow, the operator may be obliged to move the controller several points before the motor will start, and there will then be fewer points remaining for speed control. A bridge motor is seldom "plugged," the motion usually being checked by a foot brake, so that a resistor allowing full-load current is satisfactory.

On trolley motions the starting torque and current vary more in proportion to the load, and a resistor allowing less than full-load current is desirable. The trolley motor is usually "plugged" for making quick stops, and the resistor should limit the current to a safe value for the motor under this condition. Low speeds with light loads are also necessary on some trolley motions where it is necessary to place loads accurately. A resistor that will allow half full-load current on the trolley motion is desirable from all three points of view, viz., starting, speed control and "plugging."

On the hoist motion the resistor should allow at least sufficient current on the first point in hoisting to release the brake, and also to give sufficient torque to prevent the maximum load from overhauling, especially where there is no mechanical lowering brake.

The efficiency of a well designed crane may be as high as 70 per cent. The torque and current required to hoist the full load on this crane will be $1/0.70$ or 143 per cent of that which would be required to hoist the load if friction were not considered. In lowering, only 70 per cent of the torque, due to the actual load, will be available, so that the lowering torque is about one-half of the total hoisting torque. ($70/143 = 0.49$ or 49 per cent). While the current required on a series motor to give one-half full-load torque will be somewhat more than one-half full-load current, it is found in practise to be satisfactory to use this value of current on the first point hoisting, as the motor rating should be somewhat more than that required for merely hoisting the maximum load of the crane, in order to allow for acceleration.

This value of the resistor will give a fairly low speed when hoisting a light load, which is an important consideration in a hoist controller. Assuming the light load hoisting current to be about one-quarter of the full-load current of the motor, and referring to the characteristic curve of a Westinghouse No. 7-K d-c. series-wound motor rated at 27½ h. p., 230 volts, the current required would be about 28 amperes. The speed of the motor at full voltage with this current would be 1200 rev. per min. The value of the resistor to allow half full-load current, neglecting the resistance of the motor itself, which is comparatively small, is about 4 ohms. The voltage drop in the resistor is then 28×4, or 112 volts, leaving 118 volts on the motor. The speed will then be $1200 \times 118/230 = 615$ rev. per min. The full speed of this motor is 535 rev. per min. This will be satisfactory in most cases, though there are cases where a much lower speed than this may be necessary, as in the case of foundry controllers where light flasks, or moulds, must be carefully lifted to prevent shaking out the sand. For such service a higher ohmic value of the resistor may be necessary, but if there is danger of the heavy loads overhauling, other provisions, which will be referred to later, will be required. It is of course possible for the operator to move the controller over several points in hoisting the heavy load, but in so doing the number of speed control points remaining is thereby reduced.

As a compromise value for the ohmic value of the resistor, where the manufacturer may not always know the service in which the controller and resistor will be used, about three-quarters of full-load current can be allowed to flow on the first point. This will give sufficient protection if the motor is "plugged" by bringing the controller to the first point in the reverse direction while the motor is still rotating. If the efficiency of the motor is 85 per cent, the back e. m. f. of a motor wound for 230 volts will be nearly 200 volts ($230 \times 0.85 = 195.5$). At the moment current is applied to the motor in the opposite direction, the line voltage will be added to the back e. m. f. of the motor, and there will be a total pressure of 430 volts to force current through the motor and resistor. The value of the resistor to allow three-quarters of full-load current is about 2.7 ohms for the motor to which reference has been made. The current that will flow will be about one and one-half times full-load current ($430/2.7 = 159.3$ amperes. $159.3/112.5 = 1.43$). It is true that on account of the high speed which a series motor will reach on light load, there is a tendency for the voltage to go to a higher value when the field strength is increased by the current that flows when plugging; but the speed of the motor will be reduced about as fast as the field magnetism will build up, so the above voltage may be considered to be about the maximum, and it is the voltage that exists at the moment of reversal. This current will not damage the motor as it must be designed to withstand acceleration peaks as high as this.

The speed reduction obtained with a resistor as just described can be stated as being about 50 per cent for average load conditions. In the case of the Westinghouse motor to which reference has been made, a resistor of about 2.7 ohms would be used. A drop of 50 per cent in the resistor means that the current would be $115/2.7 = 42.6$ amperes. $42.6/112.5 = 37.8$ or about 40 per cent of full load, which may be considered average load conditions. The motor would run at 850 rev. per min. at this load with full voltage, so that the actual speed would be 425 rev. per min., since there is only half voltage applied to the motor.

In order to secure lower speeds with light loads than can be had with a resistor in the motor circuit, another resistor is shunted around the armature. On manual controllers this can usually be done by adding another contact finger and segment. This has the effect of reducing the voltage applied to the armature and at the same time it increases the field strength. Reductions in speed as much as 90 per cent can be secured in this manner with light loads. Any value of resistor could be used as all of the regular starting resistor is also in the circuit, and any speed could be secured by adjusting the armature shunt. However, if it is made too low, there may be too high a current in the armature and this resistor if the controller is quickly brought to this point with the motor at high speed. As explained in connection with the current values in plugging, the back e. m. f. may be about 200 volts. It is customary to use a resistor value so that the current will not exceed one and a half times full-load current. For the Westinghouse motor already referred to, with a full-load current of 112.5 amperes, the resistance would be $200/168.75 = 1.18$ ohms. In practise it could be somewhat less than this, as the motor would have slowed down somewhat and the back e. m. f. would be correspondingly reduced by the time the armature shunt point was reached. Adjustment of this resistor in the field could be made to suit the actual requirements of speed, load and current allowable.

The resistor values just described are for manual controllers. On magnetic contactor controllers it is customary to allow three-quarters of full-load current to flow on the first point in order to provide protection to the motor when plugging. On most crane controllers full-speed control is used, but the acceleration relay for the first resistor contactor should be set to operate immediately upon closure of the circuit, so that if necessary to secure more torque to hoist a heavy load, or for any other reason, the operator can close this next contactor by means of the master switch. However, the first acceleration relay should be adjusted to prevent the closure of this first contactor in "plugging," if the current is much above the current in starting from rest, so that the "plugging" current will be limited to about one and one-half times full-load current as previously explained.

Resistor Carrying Capacity

The current-carrying capacity of the resistors is another point for consideration. While there is a number of classifications ranging from light starting duty with current on 15 seconds out of four minutes up to continuous duty, there are two classifications that meet the average crane service. The first is light intermittent duty good for one minute out of four minutes, and the second is heavy intermittent duty good for two minutes out of four minutes. These are both on the basis of allowing about three-quarters full-load current on the first point. The first is known as the Electric Power Club rating No. 53, and the second as No. 73. Special cases may require more or less capacity in the resistors. Little is saved on small motors by reducing the capacity below the heavy duty rating, and the use of the heavier duty resistor makes the controller safer for conditions of operation which cannot be foreseen at the time of installation.

On manual controllers there is considerable advantage in having the resistors mounted in the same frame with the controlling elements as there is less wiring required in the crane cab. In all such cases, however, the resistors should be easily removable, both as a unit and as individual units, so that replacements can be easily made.

Controllers with Dynamic Braking

There are two classes of controllers with dynamic braking, first, those used for heavy bridges or trolleys where in either direction it is necessary to dissipate the energy stored in them during acceleration, and second, hoist motions where only in the lowering direction must the energy stored in the load during hoisting be dissipated. In the first case the energy is represented by the well-known formula $\frac{M V^2}{2}$, where M is the mass and V the velocity or speed in feet per second. This energy is small, on ordinary cranes, in relation to the energy required to accelerate and drive these motions. "Plugging" is much used on trolley motions because of its effectiveness and absence of any additional control apparatus. On high-speed trolleys of ore bridges, the proportions of this energy to the energy for accelerating and running is much greater, and a controller with dynamic braking may be desirable to reduce the current consumption and provide graduated braking to give smoother operation. On hoist motions the energy to be dissipated is represented by the formula $W \times S$ where W is the weight of the load in pounds, and S the distance in feet the load has been lifted. In lowering, friction of the gearing, bearings, ropes, etc., absorbs part of the energy stored in the load. On a crane hoist having an efficiency of 70 per cent, it has already been shown that the torque in lowering is about one-half that required in hoisting, so the energy is in like proportion.

Direct-current motors are best adapted to all forms of dynamic braking control. A series-wound motor is not well suited for controllers of the first class, where the braking is required in either direction of travel. A series generator is not a very stable machine, especially when operating under widely varying speed and torque conditions. Furthermore, the switching of connections necessary to cause the current to flow in the armature and field in the proper directions for either running or braking, whether in the forward or reverse direction of the machine, makes a complicated controller. By using a compound motor the shunt field will give the initial magnetism in the field without regard to the speed of the armature, which is not the case with the series field. It is usually sufficient to use only the shunt field excitation, and the dynamic braking connections are simple, as it is only necessary then to connect a resistor around the terminals of the armature. This resistor may be variable to give graduated braking torque. If it is necessary to include the series field in the dynamic braking circuit in order to get increased torque in braking, the shunt field should also be used to give the initial magnetism in order to cause the dynamic braking current to build up promptly under all conditions of speed. It is of course possible to excite the series field separately from the line, and so to have the same advantage as if a shunt-wound field were used, but waste of power in the resistors necessary to do this is objectionable. Usually it is desirable to continue the dynamic braking action at the "off" position of the controller, and in such cases means must be provided for automatically disconnecting the series field from the line when the motor has about come to rest, which complicates the controller. Where a series motor must be used, a so-called "teaser" circuit can be applied to the series field, so that a small percentage of full-load current will flow that will enable the motor to build up the dynamic braking current. There is still the objection that such a controller is complicated, and simpler means are usually to be preferred.

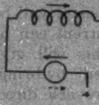

Fig. 1

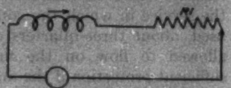

Fig. 2

A simple arrangement for securing dynamic braking with a series motor operating in either direction is to use a resistor shunted around the armature as described in connection with plain controllers. The armature will force current through the resistor across its terminals until it has slowed down to a point where its back e. m. f. is equal to or below the voltage applied to it, and it will then continue to run at a greatly reduced speed, so that it can easily be stopped by disconnecting it from the line. A magnetic friction brake may be necessary finally to stop the motor, but on account of the greatly reduced speed the energy to be absorbed by the brake is small. Several points of shunted armature, obtained by varying the resistance, should be used to enable the speed gradually to be reduced without exceeding a safe current in the armature.

Alternating-current motors are not well adapted for use on motions requiring the motor to be used for slowing down and stopping. It requires direct current for energizing the primary circuit during braking, and where alternating-current cranes are installed, no suitable provision for direct current for this purpose would be available, nor would the braking action be as effective or as easily regulated as in the case of the direct-current motors.

It will be seen that this class of controllers with dynamic braking will usually require some application of power from a source outside the motor to give proper braking action. If failure of the power supply should occur at the moment the retarding action was to be applied, either in plugging, dynamic braking or applying a shunt to the armature, failure to stop the motor may cause an accident. Where a series field is connected in the dynamic braking circuit there would be a continued braking action, provided the conditions of speed had been such as to cause it to begin. But, especially in magnetic controllers, which require power to close the contactors, failure of the controller to close the proper circuits may also result. Therefore in all cases where there is any hazard involved if the motor cannot be stopped through its own action, it is advisable to use a friction brake also. A series-wound brake is always the safest, but if the fluctuations in current are too great to permit a series brake to be used, a shunt-wound magnetic brake should be used for safety. If this is connected across the line permanently, so that it sets only in an emergency, the wear on it will be negligible, and it will be in good condition to perform its function as a safety device if occasion demands it.

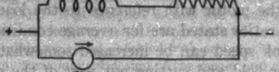

FIG. 3

DYNAMIC BRAKING LOWERING

It is on the hoist motions of cranes and similar machines that controllers with dynamic braking find their greatest application. Since the advent of the present system of control here described, in which the controller applies power for lowering light loads, as well as enables the motor to regulate the lowering of heavy loads, the various forms of mechanical lowering brakes for direct-current cranes have been practically eliminated, together with the expense for their maintenance and adjustment. A series motor has always been considered ideal for the hoist motion. It lends itself readily to the requirements of dynamic braking in lowering, for the reason that its back e. m. f. is in the right direction for lowering without complicated switching connections in the controller.

In the simple diagram shown in Fig. 1, the current in hoisting flows in the direction of the full arrows. The back e. m. f. of the armature is, of course, in the opposite direction as shown by the dotted arrow. In lowering, the armature will rotate in the reverse direction, and the back e. m. f. will be opposite to that first mentioned and current will flow in the same direction as it would in hoisting. This fact helps to simplify the circuit connections required in changing from hoisting to lowering. The connection between one side of the armature and one side of the field is fixed, and this lessens the chances of an open circuit in the controller or wiring of the crane. To complete the dynamic circuit for lowering, we refer to the diagram in Fig. 2.

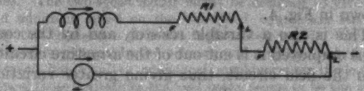

FIG. 4

The circuit is closed through a variable resistor R-1, so that the speed in lowering may be regulated. The value of this resistance depends on the speed desired. The current in the circuit varies with the overhauling load. This circuit is not yet complete, as on an electric crane provision must be made for lowering the empty hook, which may not overhaul the hoisting mechanism. This requires application of power from the line, and we add to the circuit as indicated in Fig. 3.

The series field will now be separately excited from the source of power, and under any condition of load on the hook, a definite amount of field excitation will be assured to enable the armature to generate current. In starting from rest, current will flow in the armature in the direction indicated by the full arrow, and will continue in that direction until driven by an overhauling load sufficiently heavy to overcome the friction of the hoist, and to drive the armature at such a speed that its generated e. m. f. will be greater than that applied to it, when current will flow in the opposite direction. The field strength, and consequently the speed of the armature with any load, depend on the value of resistance R^1. In practise this is found to be about one-half full-load current to give the necessary speeds for light and heavy loads. This same resistor can be used in the hoisting direction, for it meets the requirements of starting and speed control as explained in connection with plain controllers mentioned in the first part of this paper. It will be easily seen that the essence of this system is to excite the series field separately, and so obtain somewhat the characteristics of a shunt-wound motor, which is easily convertible into a generator. There is a great advantage, however, over a shunt motor in the fact that once the motor is started it can easily supply its own field excitation, even at low speeds, because of the variable resistor R^1, and thus failure of the supply voltage does not cause the loss of ability to slow down and stop the motor.

In Fig. 3, no provision is shown for limiting the current in the armature during acceleration. This is provided by another resistor, R^2, which is connected as shown in Fig. 4.

This is also a variable resistor, and by the connections employed it is cut out of the armature circuit and into the field circuit, thus giving greater variation in the speed control. The connections shown are for the last point of the controller, the arrows being considered as moving along the resistors from points marked "*F*" to points marked "*L*" as the controller is brought to the full-speed position. The ohmic value of resistor R^2 should be sufficient to limit the current at the start to suitable amounts in the two parallel circuits, viz., armature and field, to give enough torque to start the motor.

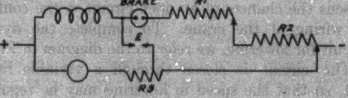

FIG. 5

It is necessary to use a magnetic friction brake for holding the load suspended, and also for bringing the load to a final stop.

Dynamic braking can reduce the speed of a lowering load to a low value, it is true, but never to a definite stop if there is an overhauling load. A series brake is used on most hoists because it offers the greatest protection if the motor circuit opens accidentally. It is also quicker acting than a shunt brake and requires no additional control wires. It is connected in the field circuit as shown in Fig. 5.

It will be noted that there is an unbroken circuit from one side of the armature through the series field and brake in either hoisting or lowering, so that the chances of losing the dynamic braking circuit by any failure in the circuit-closing contacts of the controller are limited to the connection between the other side of the armature and the brake. On magnetic controllers a spring or gravity closed contactor *E* is connected in the circuit so that any failure of voltage, or the failure of the hoisting or lowering contactors themselves, will cause the closure of a safety dynamic braking circuit independent of the regular controlling circuits. On manual controllers a similar connection is made in the controller at the "off" position.

It will be noted in Fig. 5 that another resistor R^3 has been added. This is necessary in order to secure the release of the brake under all conditions. On a manual controller especially, if the resistor R^2 were cut out too rapidly, the armature might not accelerate quickly enough, and being in a parallel path with the field and brake, would take most of the current if this resistor R^3 were not used. The brake would not release and with the low field current the armature current would reach a high value. The addition of resistor R^3 causes a more equal division of the current at the first point when starting, and insures the release of the brake even when the operator moves the controller on rapidly. This resistor R^3 also limits the current when the controller is brought to the "off" point quickly, and when the emergency circuit is closed. Theoretically this resistor should be gradually cut out of the circuit until at the full-speed position the armature would be directly across the line. If this were done, the speeds in lowering light and heavy loads would be very nearly the same, and on the heavier overhauling loads some current might be returned to the line. On manual controllers, however, the expense of the additional contact devices necessary is not warranted. On magnetic controllers such provision can more easily be made by the addition of the necessary contactors, and means can also be easily provided for insuring the release of the brake before the resistor is short-circuited. However, it has been found that unless a certain amount of resistor R^3 is left in the circuit, there will be a tendency for the motor to "hunt," or have an unstable speed for a time, due no doubt to the high armature current flowing at this time, while the field current is comparatively low.

If the current in the field on the last point is limited, by the combined resistors R^1 and R^2, to one-half full-load current, and the resistor R^3 adjusted to give proper operation of the series brake, the speed in lowering the light hook is about 1½ times the rated full-load speed of the motor, while the speed in lowering the full load of the crane is about 2½ times the rated speed. These values may vary with different conditions of friction, number of reductions in gearing and ropes, and the size of the motor with reference to the load upon it, but the ratios stated are for average conditions. The light-hook speed can be increased somewhat by using a weaker field and cutting out part of the resistor R^3 as indicated, but this adds considerable expense for the additional apparatus and is necessary only in special cases. A shunted armature connection can easily be added for the hoisting direction when necessary to secure unusually low speeds at light loads, as already explained in connection with plain controllers.

It should be noted that the combined action of dynamic braking and the friction brake at the "off" position gives double protection in preventing the load from lowering. This combined effect is had also with magnetic controllers in case of failure of voltage or failure of the hoisting or lowering contactors to close and remain closed at the proper time. On manual controllers failure of the voltage will not cause the opening of the dynamic braking circuit as in the case of the magnetic controller. The fact that there is always a dynamic braking action at the "off" position relieves the friction brake of a great part of the work of bringing the motor to rest. In this system of control, the fact that the number of places is few at which it is necessary to open the circuit in changing from hoisting to lowering, makes it a very safe system of control for hoists. All these points have been well proved by the number of controllers of this type now in use. In fact, it has become the standard system of control for the hoist motion of direct-current electric cranes.

Discussion

SELECTION OF ELECTRICAL APPARATUS FOR CRANES (McLain)

AUXILIARY ELECTRICAL EQUIPMENT FOR MOTOR-OPERATED CRANES (Eastwood), and

ELECTRIC CRANE CONTROLLERS (Schnabel),

C. A. Bird: Referring particularly to Mr. Eastwood's paper on brakes, we might add the subject of weather-proof coils. Cranes at steel mills usually are used out of doors, and are subjected to weather conditions that are rather severe, and the design of the brake might be well considered along the same lines as those of the motor. This will refer to the linings as well.

On the limit switches, I have seen a lot of well-known 2 by 4 type short-circuit in the armatures and reduce the efficiency of the motor.

I cannot understand why the dynamic braking type is not used more than it is. It is certainly a device that will give the protection that is desired on crane hoists.

On crane protecting panels, there is no question but that they are being used more and more. They provide a very convenient means of combining all the devices for protection of cranes all in one unit. The practise now is to enclose the steel panels in a steel cabinet and lock it so the operator cannot interfere with the setting of the relay.

H. D. James: Mr. Eastwood states: "It is difficult to secure more than a 65 per cent speed reduction when lowering a heavy load without dangerously overloading the field windings." These data seem to be based on the assumption that in dynamic brake lowering not more than full-load current can be passed through the fields. Well designed motors will stand more current than this and in many cases 150 per cent full load may be used. The minimum speed obtained with any particular motor depends upon the combined design of the motor and controller. Where low speed is an important factor, it is very desirable for the engineers designing the control to work in close contact with the motor designers in order to obtain the best results.

Under the head of A-C. Magnetic Friction Brakes, the assumption is made that the lowering speed under load will not materially exceed the synchronous speed of the motor. This assumption is true only when the secondary of the motor is short-circuited. Much higher speeds can be obtained with resistance in the secondary if a load brake is not used. For ordinary shop cranes the most common and perhaps the best practise at the present time is to use a load brake.

Dynamic braking for a-c. hoist motors may be obtained in any of four ways: (a) Exciting the stator with d-c. power; (b) Using a two-speed motor; (c) Plugging the motor in the reverse direction with resistance in the secondary for varying the slip; (d) The use of a frequency changer in the primary.

All four of these methods are in successful operation but are not ordinarily applied to cranes.

The d-c. system of dynamic braking provides for motor operation at low speeds where power is required to lower the hook. As soon as the load changes from positive to negative, the motor speeds up and the braking operation automatically takes place without changing the motor connections. This arrangement permits the gradual lowering of the hook under all conditions of load. When a-c. motors are used the use of d-c. power in the field or of plugging the motor does not provide for the gradual lowering of the hook without changing the motor connections. The two-speed motor might be designed to give the desired minimum speed on the low-speed connection but ordinarily this connection gives too high a hook speed. The use of a frequency changer in the primary will give the desired low hook speed but involves additional machinery on the crane. In view of these limitations the load brake seems to be the most desirable practise at the present time.

I agree with the author that every crane should be equipped with a limit switch that opens the main motor circuit at the upper limit of travel and is operated by the block or hook. In many cases the head room under the crane is so limited that it is difficult to avoid running into the limit switch and I see no reason why this switch should not be designed in as durable a manner as the other portions of the control equipment so that it will withstand repeated operation.

I do not believe that the design should be arranged to cause inconvenience to the operator in resetting this switch, particularly where the head room of the crane is limited. We have crane equipments in our own factory where the limit switch must be operated on nearly every hoist motion. This is an extreme case but there are many other applications requiring the frequent operation of the limit switch. If we require the trolley to be run over to the cab in order that the operator may reset the limit switch we impose a hardship and where this operation has to be performed with a heavy load on the hook we may introduce a hazard out of proportion to the results obtained.

Elevators and other hoist devices similar to cranes are provided with a durable limit switch which may be operated every time the car reaches either limit of travel.

It seems to me that in condemning the use of springs the author is condemning all control apparatus. I do not know of any normal design of control where springs are not relied upon for maintaining contact pressure between the current carrying elements of the switching mechanism. A failure of these springs might result in serious accidents. The reliable operation of control apparatus is a proof that springs when properly designed are reliable. There is no mystery about the proper design of springs. They are composed of the same kind of material we are accustomed to using in other parts of the design and under other conditions. It is well known that if the fiber stress in the metal, whether it is a spring or some other part of the apparatus, is in excess of a safe limit that breakage may result. The spring failures can usually be traced to improper design. A great many springs are not accurately calculated but are the result of a cut-and-dried process. The calculations of a spring are more difficult than an ordinary beam and some designers have not had the necessary experience to properly determine their fiber stress.

I am a strong advocate of the use of springs instead of gravity as they have very little inertia, are compact and can be worked into a design to much better advantage. They are not affected by vibration. The magnet brakes we use for holding crane loads are set by springs. Why discriminate against the use of a spring as the actuating means of a limit switch when we use springs in the current carrying parts of this limit switch and we use springs for setting the magnet brake which is operated by the limit switch and use springs in all other portions of the equipment including the motor brushes which form part of the dynamic brake circuit? I do not feel that I can express myself too strongly on this point.

P. Trombetta: I don't quite agree with the gentleman that just spoke in that a spring is like a beam. The making of a beam does not involve the process of hardening and proportioning the carbon, etc., while making a spring is almost a matter of art. There are only certain companies that make springs, and sometimes you cannot even rely on those springs. I know of an instance where a company tried to make springs by themselves for use in a certain truck; they tried for several years, and so far as I know, never succeeded in making two springs alike. Probably every one of them gave trouble when they were in use, and I can't see how the spring may be compared with a beam. I must agree with him, however, that perhaps too little attention is given to their design, and also that the spring in a good many cases is the only solution of the problem, because it does not introduce additional masses which have to be accelerated whereas balancing by gravity, by eliminating one difficulty, we insert another, which is inertia, and you often find that the cure is worse than the disease, and consequently we may state that the spring has certain places as well as gravity has certain places in engineering and there are certain applications where only gravity can be used, for instance, in elevators, springs would be the best thing there is for such services, but we can't hope to find a spring that would be as long as an elevator shaft. It must be understood however, even elevator balancing weights are very detrimental since they must be accelerated and retarded just as the elevator itself.

Albert J. Acker: Mr. Eastwood made a statement that a band brake doesn't exert a braking torque in the hoisting direction, that is, with the motor armature operating in the hoisting direction. That is true if the band is anchored at one end only, but it is possible to make a band brake with both ends attached to the lever and have it exert equal torque in both directions, and therefore stop the motor just as promptly when it is revolving in the hoisting direction as it does in the lowering direction. A further advantage in such an arrangement is that the same band can be put on the intermediate shaft brake or the second shaft brake, and anchored at one end and give interchangeable brake parts for both of those brakes.

About limit stops, Mr. Bird stated that he couldn't understand why the dynamic braking limit switch is not more widely used than it is. I think I can answer that question. The reason is because there are so many varieties of cranes, so many different numbers of parts of rope, two parts, four, six, eight, ten parts, and all the different styles of lowering blocks, and it is difficult to put on those dynamic braking limit stops in many cranes. That is, to find the room to put them. In two respects, it is difficult to find a place to put them on the trolley itself, and it is difficult to hang the operating or tripping mechanism above the lowering block.

Another difficulty with limit switches is that the crane hoist is so frequently used for something else besides hoisting; to pull a car or to drag something along the ground, and the rope is pulled off at a sharp angle, and any mechanism that is put above the lowering block is likely to be bent or broken when the crane is used in these unusual ways. You all know that that is done very frequently. In an attempt to make a limit switch that could be tripped by the lowering block and yet not be rigid, so when the rope is pulled off at an angle it won't break, the scheme of using a mercury tube has been tried, the idea originating from its application to rubber calendar work. You may know that a rubber calender is very dangerous to operate and there is usually a board across for a man to butt his head into for a quick stop if he catches his hands. This board trips a switch of some kind. Mercury switches have been used for that purpose, a little tube no larger than a 30-ampere fuse with contacts arranged in it, and a little puddle of mercury. If it is tipped one way it makes a contact, and if tipped the other way it breaks it. That same tube applied to a crane limit switch works out well in many instances. It can be put in a little box with an arm sticking out from it and hung so the lower block coming up must tilt that lever arm. Now that can be hung perfectly free and no matter how the ropes pull off, it cannot be bent or broken, yet when the lowering block comes up and tilts it, it will trip the limit switch. Of course that will have to operate on control circuits, not on the main circuits. For some cranes this is a valuable idea, because it is so difficult to bend or break.

It is possible to get on the market now a tube filled with inert gas so the contacts don't blacken after many makes and breaks.

Electric Power Application to Passenger and Freight Elevators*

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This Committee has been requested to report on the application of electric power to passenger and freight elevators. An enormous amount of electric energy is used for the operation of elevators and it is therefore fitting that the problem be studied from a power economy standpoint as well as from the more important standpoint of protection to life and limb.

It is assumed that the reader knows little of this subject and that practically nothing up-to-date has been published. It is not believed that the reader will be particularly interested in accurate technical details, but that he will want to know the range of application of elevators, their motors, controllers and all safety appliances as represented by best present practise.

Included in this report are six chapters as follows:

I. History and service requirements.
II. Types of elevator machines and the limitation of each.
III. Charateristics and limitations of d-c. and a-c. motors.
IV. Elevator controllers.
V. Brakes and other safety accessories.
VI. Power consumption.

I—HISTORY—SERVICE REQUIREMENTS

HISTORICAL

THE history of the elevator dates back to 236 B. C. which date is mentioned by Vitruvius describing an elevator built by Archimedes in that year. This "elevator" was operated by man-power applied to a capstan revolving a drum on which hoisting ropes were wound.

According to Prof. Coburn, of Philadelphia, who has made extensive archaeological studies in Palestine, the palace of Nero had three elevators.

It is reported that Prof. Commadatore Boni, the celebrated Italian archaeologist, while exploring some underground passages near the north rostra of Caesar, discovered twelve small galleries which he claims are traces of a former system of elevators, as in each room there are grooves through which ropes passed and stone supports for wooden poles are fixed vertically inside the passages.

An early mention of an elevator is made in a letter of Napoleon I to his wife, the Archduchess Maria Louise.

A Brussels paper not long ago stated that the apparatus which takes an occupant from the ground floor to the top of a building in a few seconds is not a new invention, as an ingenious contrivance was constructed in the seventeenth century by Velayer of Paris who called his invention "the flying chair." It was not merely a toy but became very fashionable among the rich people on account of its utility. It consisted of a chair hung by a rope passing over a pulley and counterbalanced by a weight. It continued in operation until a serious mishap occurred to the King's daughter at Versailles.

No doubt the elevator as we know it evolved from the so-called" flying chair." Only since 1850 has real progress been made in elevator development. In that year George H. Fox made an elevator operated by the motion of a vertical screw, the nut being carried on the cage.

The steam elevator, now practically extinct, was introduced over half a century ago. This stimulated increased building heights but successful service was limited with this type of machine. About 1880 the hydraulic elevator came into use and it practically superseded the steam machine at that time. However, building heights were limited by brick bearing walls inasmuch as steel-framed structures were not known. The introduction of steel building frames made the limit of building heights a commercial rather than an engineering problem.

The electric elevator was invented about 1885 and the first installation was made in 1887, but it was not developed sufficiently for extensive use until approximately the year 1893. Still, many hydraulic elevators were installed, although many were equipped with electrically driven pumps. Even with this arrangement the hydraulic elevator consumes more power than the electric elevator. During the past ten years there has been a decreasing number of hydraulic elevators installed. The electric machine has practically superseded all other types. This is true because the electric elevator is more readily equipped with suitable safety features, it occupies less space in the building, its initial cost is less, it is more easily controlled, and the power consumption and repair bills are smaller.

It is estimated that in any large city more people are carried daily by passenger elevators than by all

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*A paper prepared under the auspices of the Subcommittee on Elevators of the Industrial and Domestic Power Committee:
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street cars and subways combined. It is extremely important therefore that elevator travel be safe. It is almost equally important that for the service required the electric power consumption be reduced to a minimum.

SERVICE REQUIREMENTS

1. *General Requirements.* The initial elevator problem is one of service. So many factors enter into this problem that each individual case must be considered as a separate problem in itself. However, some accepted general rules may be stated for the guidance of elevator selection.

The service to be rendered depends upon the number of passengers, or the weight and bulk of freight to be carried, and upon the number of floors served. It is limited by the time taken for loading and unloading as well as by the time consumed during acceleration and retardation, and by the time consumed during travel at full speed.

For many stops per car-mile the important factors are quick starting and stopping, and quick loading and unloading. For few stops per car-mile the more important factor is higher running speed. In many installations accurate stopping is also extremely important.

We can consider elevators as vertical railways, running express or local, as the service may require, and when they are so arranged that they carry the number of people that arrive at or depart from the building in a given time, and distribute them on the various floors, or bring them to the street level, the elevator service may be considered 100 per cent of that required. The same applies to material-carrying elevators relating to the service of delivering incoming and outgoing material so that it does not accumulate anywhere.

In order to give passenger elevator service in a building, it is necessary to consider the number of persons that enter and leave the building, morning, noon and night, and also the number of people that enter and leave between these times.

The building height and floor area are not the only things that are needed to determine elevator service, although they must be considered in connection with the local regulations with reference to speed.

The elevators must have a given capacity in pounds and should be capable of running at a certain maximum speed with this load.

The passenger elevator car should be constructed with reference to its opening towards the hall so that a number of persons can enter or leave at the same time, making a car rather shallow in depth, but wide. The dimensions of a freight elevator car depend much upon the material to be handled, but quick loading and unloading should be a consideration in the determination of the car size.

Elevators should be capable of accelerating and retarding as rapidly as local power conditions will permit with, however, due consideration of effect on passengers and power consumption during starting and stopping.

The number of elevators required of the express or local type should be determined from the number of people that it is necessary to carry per hour, and the grouping of these elevators should be considered with reference to the entrance to the street or streets so that the movement of traffic may be distributed to best advantage.

Elevators should be durably and economically constructed, so that if ordinary care is exercised in their maintenance, only small inexpensive, interchangeable parts need be replaced in order to keep the elevators in fit condition for continuous service. The major parts should last indefinitely without replacement.

The direct-current elevator was the first to be perfected because of the fact that we had no suitable a-c. motor for elevator service prior to 1905. Even after the development of the a-c. induction motor the d-c. motor was better suited to elevator service due to the ease with which speed control can be obtained under varying loads. However, it has been found difficult to obtain direct current in outlying sections of our cities especially, and in some cities direct current is unobtainable. It is therefore necessary to use such power as is available, and in the application of the alternating-current motor to elevator work of the higher speeds, it has been found that it cannot compete with the direct-current motor in the present state of the art due to the inherent characteristics of the single-speed induction motor. There are, however, several types of multi-speed alternating-current motors especially designed for elevator service that are performing very satisfactorily on speeds up to about 300 ft. per min. and when properly installed, the service given is comparable with the direct-current elevator of the same speed. However when applied to higher speeds, a number of complications arises because the alternating-current motor does not lend itself to the refinement of control possible with the d-c. motor.

2. *Speeds and Capacities.* Heights of buildings are not limited by weight and speed limitations in elevator equipment. Elevators have been built for speeds up to 700 ft. per min. for passenger service, up to 30,000 lb. lifting capacity for freight service, and up to 100,000 lb. for special forms of electric hoists such as car dumpers.

The speed of the elevator for any particular service is very difficult to determine satisfactorily to everyone as it is more often personal opinion than engineering judgment that decides this detail.

As a general guide for estimating, the following will serve as representative of present practise:

Passenger Service—Office Buildings, etc.

Total Travel	Maximum Car Speed
Feet	Ft. per min.
0 to 50	50 to 300
50 to 75	300 to 350
75 to 100	350 to 400
100 to 150	400 to 500
150 up	500 to 550

Express service—550 to 600 ft. per min.

The above is for direct current and for operator-controlled cars. For automatic push-button service 300 ft. per min. is usually considered the limit of speed, as the automatic elevator is inherently a time waster inasmuch as the person within the car has complete control and runs the car without regard to the floor demands. It should be noted that 700 ft. per min. is not given in the table principally due to the fact that many state and city codes limit the speed to 600 ft. per min. For alternating current 400 ft. per min. is considered the limit although very extensive developments are being carried out at the present time by many manufacturers, the results of which they hope will make it practicable to use a-c. motors in connection with elevators traveling at a higher rate of speed.

The values in the above table are entirely dependent upon the average number of stops per mile of car travel. For example, in department store service where stopping at every floor is required for sales reasons, 350 ft. per min. is the maximum desirable speed because above this the car would not attain full speed between floors and therefore would give very inefficient operation; 250 ft. per min. is about the accepted correct average speed for this service. In office buildings of eight stories or less, the number of stops per mile generally ranges from 150 to 200. In office buildings above eight stories the number of stops will range from 125 to 175 per mile for local service, while for express service we can expect 50 to 150 stops depending upon whether service is given to several upper floors or to only a club or restaurant on one floor.

The capacities of passenger elevators vary from about 1000 lb. in residences to 5000 lb. in department stores, and from 2000 to 3000 lb. in office buildings. The capacity determines the car size which should be of sufficient floor area to provide not over 75 lb. per square foot. This is an accepted standard throughout the United States.

The number of elevators required to supply a given service is very difficult to determine accurately because each building is an individual problem in itself, due to the large variation in the demands such as internal traffic, insurance office traffic, consulting office traffic, etc. Consequently we can use only similar buildings for estimating an approximate average. The following method may be used as a guide for determining the number of elevators required in a building of known dimensions.

The population can be estimated from the rentable area as follows:

New York City—75 to 100 square feet per person.
Other large cities—100 to 130 square feet per person.
Small cities—125 to 150 square feet per person.

Total travel in feet if not known can be estimated by assuming 17½ feet for the first floor and 12½ feet between other floors.

Floor area of car platform:

27 sq. ft. for 2000 lb. for medium height buildings.
33 sq. ft. for 2500 lb. for standard office building capacity.
40 sq. ft. for 3000 lb. for special service where a lift for safes is required or the time schedule of leaving the first floor is not a feature.

The normal capacity of a car in passengers without crowding is determined by allowing two square feet per person including the operator.

The estimated time for synchronizing the cars, loss in time due to accelerating and retarding, loading and unloading at the first floor is 27½ seconds. The estimated time for accelerating and retarding, loading and unloading for each floor above the first is 7 to 8 seconds, or if positive door locks are used, 8 to 10 seconds.

The estimated time required to empty the building above the first floor usually ranges from 40 to 60 minutes.

The following is an example of an office building calculation for New York City.

Rentable area above first floor	190,000 sq. ft.
Travel first to sixteenth floors—All local	192 ft.
Car capacity. 2500 lb. 33 sq. ft.	15 persons
Speed of car	550 ft. per min.
Positive door locks used	
Time required to empty building	45 min.
Estimated stops per mile of travel	150 stops
Estimated sq. ft. per person in building	80 square ft.
Population of building = 190,000 + 80	2375 persons
Number of trips to empty building = 2375 + 15	159 trips
Time lost. Stops at first floor =[27.5 + 2	29.5 sec.
Actual running time per round trip $= \frac{2 \times 192 \times 60}{550}$	42 sec.
Total round trip travel = 2 × 192	384 ft.
The average number of feet between stops = 5280/150	35 ft.
Number of stops above first floor = 384/35 − 1	10 stops
Stopping time above first floor = (7½ + 2) × 10	95 sec.
Total time of round trip = 29.5 + 42 + 95	166.5 sec.
Total time of round trip	2¾ min.
Time required for one elevator to empty the building = 159 × 2¾	437 min.
Number of elevators required to empty building in 45 minutes × 437/45	10 elevators

From the above it will be seen that during the rush hours ten elevators with a capacity of 2500 lb. at 550 ft. per min. will give approximately 17-second service leaving the first floor. For the other hours of the day eight elevators will handle the traffic and give 20-second service from the first floor. If 15-second interval service is required eleven elevators will be necessary. This question of time interval must always be checked before definitely determining the number of elevators.

These calculations can only represent average conditions as the human element enters into the problem to a considerable degree. For example, the time the car will be stopped at a floor varies from 4 to 12 seconds depending mainly on the characteristics of the people served.

On page 59 is given a table of speeds for various rises as representative of present practise. It is interesting to note the effect of a change in speed upon the passenger-carrying rate and upon the power consumption per car mile.

Since an elevator doing local service in an office building of fifteen stories or less spends nearly as much time in starting and stopping as in running at full speed, the energy consumed in accelerating and retarding becomes an important factor. The energy required to accelerate to full speed is present in the moving system in the form of kinetic energy, but with most methods of control in use very little of this energy is recovered in stopping. The energy that must be stored in the machine, car, counterweight, cables, etc. for each start depends upon their mass times the square of the velocity to which they are accelerated.

It is, therefore, evident that increased car speeds must be accompanied by a considerable increase in the power consumption per car mile. It remains to be seen what effect a change in car speed will have upon the carrying rate of the elevator.

For the sake of comparison the foregoing office building calculation will be analyzed for a car speed of 450 instead of 550 ft. per min.

All other values except the following remain the same as before:

Speed of car	450 ft. per min.
Actual running time per round trip $= \frac{2 \times 192 \times 60}{450}$	51.3 sec.
Total time of round trip = 29.5 + 95 + 51.3	175.8 sec.
Total time of round trip	2.93 min.
Time of one elevator to empty building = 159 × 2.93	465 min.
Time required for 10 elevators to empty the building	46.5 min.
Interval of service	17.58 sec.
Estimated car miles per day (10 elevators)	120 car miles
Estimated car miles per year (10 elevators)	36,000 car miles
Estimated kw-hr. per car mile saving by using 450 ft. per min. instead of 550	0.8 kw-hr.
Kw-hr. per year saved = 0.8 × 36,000	28,800 kw-hr.
Dollars per year saved at $0.01 per kw-hr.	$288.00

The amount of saving per car mile due to the reduced speed may vary as much as two-to-one in individual cases. The above figures are merely given as an illustration and not as a guarantee in any sense of the word. The price of power at $0.01 per kw-hr. is given so that knowing the power rate in any locality the saving may be easily calculated.

The above analysis shows that the decrease in speed increases the time required for the ten elevators to empty the building from 43.7 to 46.5, or 2.8 minutes, and increases the time interval from 16.65 to 17.58 seconds, or less than one second.

The use of the lower-speed elevators increases the time required to empty the building by an amount that is probably much less than the errors that would be made in the original assumption.

This analysis is not submitted as a more nearly correct solution of the problem but is simply to illustrate the effect of changing the car speed. It is probable that if building owners fully realized how much they are paying for higher elevator speeds and how little they are really gaining by them, there would be a downward revision of elevator speeds for buildings of this class.

Freight Elevators. Freight service is extremely varied, ranging from 1000 to 30,000 lb. short and long travel, and at speeds of from 30 to 250 ft. per min. The determining of the correct freight speed is not so difficult because the service is usually fairly well known. The cost of installation increases very rapidly with increase of speed with the result that speed is often sacrificed for first cost which explains why very few freight elevators above 100 ft. per min. are in use except in plants where an enforced system of manufacture is maintained. This means really two different demands. First, for isolated installations, storage, small plants, etc., speed ranging from 30 to 100 ft. per min. and for large manufacturing plants requiring speed from 100 to 250 ft. per min.

It has been proved very conclusively that a speed above 250 ft. is not warranted except for special service because only a small fraction of the total time is running time.

The required capacity of freight elevators is usually known because the material to be handled is known. The tendency of large manufacturing plants is to use some type of power driven truck which is usually very heavy, so this demands elevator capacities from 5000 to 15,000 lb.

Service or capacity of elevators is affected by safety appliances such as door and gate interlocks inasmuch as the introduction of these devices increases the time for loading and unloading. Thus the extension of safety appliances tends to increase the number of elevators installed. This is unfortunate, but the safety consideration is so vastly important that the reduction of service efficiency is not to be deplored.

II—THE ELEVATOR MACHINE

General

The electric elevator is made up of three principal parts:

1. The car, consisting of the car frame and enclosure with such control and safety apparatus as is necessarily attached to the car.
2. The shaft work, consisting of the guides, counterweights, buffers, limit switches, etc.
3. The hoisting engine, with motor, brake, controller and cables.

The car should be made as light as practicable so as to keep down the load on the machine bearings and also so as to assist in keeping down the power consumption.

The elevator guide rails are of great importance in connection with efficient and safe operation of the elevator, as the smoothness of operation in the car is largely dependent upon good elevator guides, properly installed. The guides must be uniform in size, straight and installed in exact alignment. It is best to have the guides machined and the ends tongued and grooved for accurate connections with fish plates.

The electric elevator hoisting engine is a simple mechanism consisting of a grooved drum or driving sheave over which the hoisting cables pass from the car to the counterweight, and a mechanical brake. In most cases a gear-reduction mechanism running in oil is incorporated between the electric motor and the driving sheave.

Location

Infrequently the elevator machine is installed in the basement of a building. Probably 98 per cent of all new installations in the United States use an overhead machine installed in a room called the "pent-house" at the top of the building. Basement installations are objectionable because they require much longer hoisting cables and more idler sheaves than for overhead machines; they occupy valuable space in the basement and in many cases the actual load on the building is greater. Placing the machine directly over the hoistway imposes a load on the building equal to the weight of the hoisting machine, plus the loads on the car and counterweight ropes, whereas placing the machine below, imposes a load on the building equivalent to twice the loads on the car hoisting and counterweight ropes. Therefore, if the hoisting engine weighs less than the combined loads on the car and counterweight ropes, placing the machine overhead reduces the load on the building. This relation of weights often occurs.

Roping

The different types of machines according to roping are: Winding drum, full-wrap traction, and half-wrap traction (generally known in this country as the "V" groove traction and abroad as the "wedge drive" traction.)

The winding-drum machine predominated in earlier elevator history, but for passenger service it is gradually being superseded by either the full-wrap traction or the half-wrap traction elevator. Even for freight service many traction-type elevators are now being used. The following will give a clearer idea of the three types of elevators.

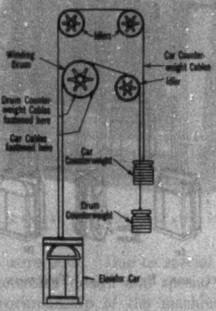

Fig. 1—Typical Roping for Overhead Drum-Type Elevator

Winding-Drum Machine. The method of roping is shown in Fig. 1. Three sets of cables are used. The first set or hoisting cables is attached at one end to the winding drum and at the other end to the car. The drum counterweight cables are also attached at one end to the winding drum but the other ends of these cables are fastened to the drum counterweight. The third set lead from the car, over idlers, to the car counterweight. The drum is machined with spiral grooves so that as the hoisting cables wind up, the drum counterweight cables unwind.

This type of elevator is limited to relatively short travels (not over about ten stories) due to the fact that the drum length becomes unwieldy on longer travels.

If the drum-type machine is installed overhead it will give remarkably long cable life because there is no possible cable creepage and the bending is always in one direction. However, if the machine is installed in the basement, reverse bends are necessary in the cables and this materially reduces the cable life. A car counterweight is used with the larger cars to reduce the load on the drum and drum bearings. One reason for the decreased use of the drum machine is because it requires a modification of the machine for each installation, as the length of travel determines the length of the winding drum. Another bad feature is that should the terminal stops and overtravel limit switches fail to stop the car at the terminals, the machine may continue to travel and finally pull the cables from their sockets.

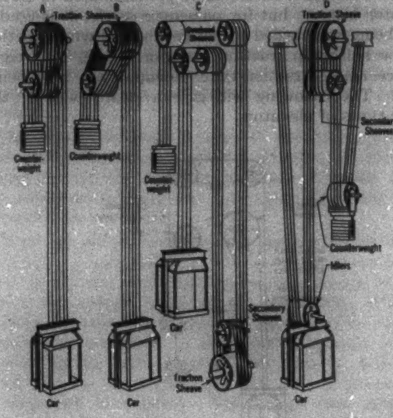

FIG. 2—ROPING FOR FULL-WRAP TRACTION ELEVATORS

Full-Wrap Traction Machine. The roping for various full-wrap traction machines is shown in Fig. 2. This machine, cabled directly one to one, or two-to-one, has the advantage of being a standard stock machine for all lengths of travel. The driving sheave has parallel round grooves, the driving of the car being dependent upon the friction between the cables and these grooves. To get sufficient traction an idler is necessary so as to get the equivalent of a full wrap around the traction sheave. A great advantage of the traction machine, both half-wrap and full-wrap is that if the limit switches fail to stop the machine at the terminals, the landing of either the car or the counterweights will slacken the cables and allow the machine to overrun without moving the car.

One possible objection to this type of machine is that the driving sheave bearing is required to take double load due to the double wrap necessary in this form of drive. This produces a somewhat lower efficiency than could otherwise be realized. Because of the round grooves the traction is limited but it does not change much with wear as it does in the case of the half-wrap traction machine.

Half-Wrap Traction Machine. For the method of roping used, see Fig. 3. It will be noted how simple the roping is, there being only two cable bends (one as the cable leads onto the driving sheave and the other as it leaves), where the driving sheave diameter is one-half the car width, although this is doubled when a deflecting sheave is necessary. However, for loads above approximately 15,000 lb. a two-to-one roping is generally used. As the car width increases to a point where it is impracticable to further increase the diameter of the driving sheave, the amount of "wrap" possible on the driving sheave decreases. Therefore in the case of wide freight cars it is sometimes necessary to use the full-wrap traction machine in order to get sufficient driving friction. The driving sheave bearing load is only one-half that of the full-wrap traction machine.

One criticism of this type of elevator is the wearing of grooves in the sides of the V, thereby reducing the pinching action, although sheaves properly machined are still in good operating condition after eight or ten years of constant regular service. Moreover the rim in which the grooves are cut can readily be made removable for replacement.

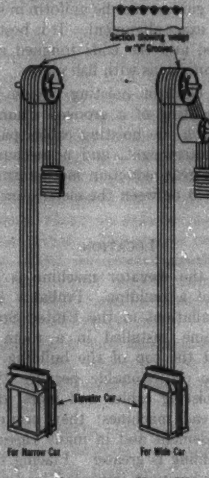

FIG. 3—ROPING FOR OVERHEAD HALF-WRAP TRACTION-TYPE ELEVATOR

The traction elevator has the advantage of being a standard or stock machine for all lengths of travel. If the limit switches fail to stop the car, the landing of either the car or the counterweights will slacken the cables and allow the machine to over-run without straining the hoisting cables.

It is still an open question whether the full-wrap or the half-wrap traction machine is the better. Cable life is generally a little longer on the half-wrap machine, but the wear of the V grooves is still a problem.

GEARING

Elevator machines have been built gearless or with the following types of gearing: Single worm and gear, single herringbone gear, tandem worm and gear, single worm and gear with external spur back-gearing, single worm and gear with internal spur back-gearing and car leveling single worm and gear.

Gearless Elevator. The gearless elevator is shown in Fig. 4. It requires a very low-speed direct-current motor, because the driving sheave diameter is usually made not less than forty cable diameters in order to obtain reasonable cable life, and therefore to obtain the desired elevator speed a motor having a speed of 65 rev. per min. or less is used. Due to this limitation, car speeds with the gearless machine lie between 400 and 700 ft. per min. It is a very smooth and quiet operating machine and gives a high full-speed operating efficiency for long travels. As yet this machine is generally built in the full-wrap traction type which reduces the full-speed running efficiency somewhat.

The low-speed motor design inherently means a very large machine and therefore to keep the size down only a small range of speed is obtained by a change in shunt field. It is therefore necessary to use either series-parallel resistors in the armature circuit or multiple voltages applied to the armature in order to obtain adequate speed control. The series-parallel resistor method is a low-efficiency method of starting and stopping. Where alternating current only is available a synchronous converter may be used. Sometimes multi-voltage control is considered, which requires a motor-generator set to supply the multi-voltage. The stand-by losses of this set reduce the operating efficiency. If direct current is available, a storage battery may be used to supply the multi-voltage.

The gearless machine roped two to one, allows a motor of twice the speed of that of the one to one for the same elevator car speed and therefore a higher speed can be used and the motor built on a smaller frame. This type of machine is usually used for car speeds of 400 to 500 ft. per min. It is a smooth and quiet operating machine. Its speed is also controlled generally by series-parallel resistors. This machine has until recently been built in the round groove, full-wrap traction type, giving ten cable bends and a lower full-speed running efficiency. There has lately been installed a half-wrap machine, reducing the cable bends to six. The number of cable bends is then equal to the one to one, so the efficiency is doubtless about the same as the one to one.

Single Worm and Gear Machine. This machine (see Fig. 5) covers a wide field of application as it is used with drum, full-wrap traction, half-wrap traction and two to one cabling, for car speeds from 50 to 500 ft. per min. In car speeds up to 300 or 400 ft. per min. it has been a standard almost ever since electric elevators were built. Due to special effort in the motor and controller design and special attention to design and workmanship of the machine and gears, some machines of this type are now working at car speeds of 600 ft. per min. with smooth and quiet operation.

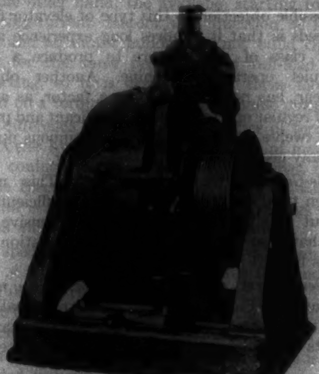

FIG. 4—GEARLESS TRACTION ELEVATOR MACHINE

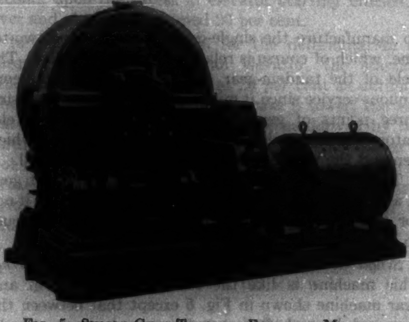

FIG. 5—SINGLE-GEAR TRACTION ELEVATOR MACHINE

While the full-speed running efficiency is less than that of the gearless machine, its actual operating efficiency with the shunt field controlled motor is usually higher on any service requiring many stops per car mile. The better operating efficiency becomes more and more of a factor as the number of stops per car mile increases. Another feature of value is that the winding sheave diameter is not limited and can in most cases span one-half of the car depth, thereby eliminating all idler sheaves and increasing the cable life.

A possible objection to this type of elevator for high car speeds is that it requires long experience and the highest class of manufacture to produce a smooth and quiet operating machine. Another objection, gear wear, has not proved to be a factor, as after six years of regular operation it is insignificant and promises to give twelve to fifteen years of continuous operation before any gear replacement is necessary.

Single-Gear Herringbone Machine. This machine has been tried extensively, giving very efficient operation, but it is understood that it is expensive to cut gears that insure quiet and smooth operation. This fact has limited its use.

Tandem Worm and Gear Elevator. The tandem-gear machine (Fig. 6) has been in use practically from the date of the earliest electric elevators and has stood its own, although at present there is a tendency to manufacture the single-gear machine roped two-to-one, which of course is relatively hard on cables. The field of the tandem-gear elevator is heavy duty continuous service since it minimizes gear pressure by using three points of gear contact. The majority of elevators used in rubber and automobile plants which demand the most severe service, is tandem geared.

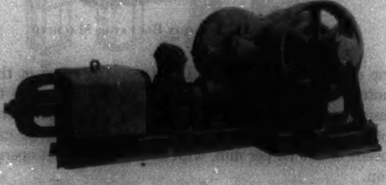

Fig. 6—Tandem-Gear Traction Elevator Machine

There seems to be an impression that a thrust gear is a poor thrust bearing, and so it would be were it not for the fact that this thrust gear delivers its thrust to lift one-half of the load.

Single Gear with External or Internal Back Gearing. This machine is like the standard single worm and gear machine shown in Fig. 5 except that between the gear and drum shafts is a spur gear reduction not ordinarily oil immersed. The reason for this is to enable a small machine to lift a heavy load where the service is intermittent and first cost is a determining factor. It is a question of judgment whether to use this type or the single-gear elevator roped two to one.

Car-Leveling Single Worm and Gear Elevator. The car-leveling elevator has a certain field where it is very essential that the landing stops be accurately within one-quarter inch, plus or minus, with the landing. This is accomplished with shunt field control of d-c. motors whereby a low enough speed with high enough torque can be obtained; or by applying a low-frequency to a regular a-c. elevator motor, or by the use of an additional small geared machine arranged to drive the regular hoisting motor and brake shoes at a low speed.

Counterweighting and Cable Compensation

To get best operating efficiencies it is essential that both of these subjects receive careful consideration. Many elevators are running today with insufficient counterweight, and with no cable compensation on jobs where the rise is great and therefore compensation should be used.

Counterweighting. It is obvious that an elevator without any counterbalance will be very inefficient because the motor horse-power required would be relatively large. It is customary therefore first to supply sufficient counterweights to balance equally the elevator car. Then enough additional weight is added to equal the estimated average load. This additional counterweight is generally known as "over-counterweight." The amount of over-counterweight is usually between 30 and 40 per cent of the maximum rated capacity of the elevator. In rare cases this amount is made 50 per cent, where full load is carried by the elevator nearly every trip. In any case the over-counterweight never exceeds 50 per cent of the rated load.

To illustrate the need of proper counterweighting, assume the following problem:

L = rated elevator load . . . . = 3000 lb.
S = rated elevator speed . . . . = 500 ft. per min.
W = over-counterweight in lb. = ?
E = per cent efficiency—Line to load.

$$\text{Then, h. p. required (theoretical)} = \frac{(L - W) \times 500}{33{,}000 \times E}$$

If there is no over-counterweight it will require 45½ h. p. (at 100 per cent efficiency) to lift the full load at full speed. At 50 per cent over-counterweight, it will require just one-half of this power. However, with more than 50 per cent, it will take more power to lower the empty car than to hoist the maximum load.

If the over-counterweight is made equal to the average load, the maximum operating efficiency is obtained.

The "line of load" efficiency varies from about 40 to 75 per cent depending upon the size and design of motors, machines and roping. For instance a worm-gear machine with a low gear tooth pitch and with babbitt bearings may not show a greater efficiency than 50 per cent, while a high-speed geared elevator with a high gear tooth pitch, roller bearings throughout and no idler sheaves, may show an efficiency close to 75 per cent.

Cable Compensation. As a rule the compensating of hoisting cables in buildings of ten stories or less is not an item. Above ten stories however, it is usually desirable to use some form of compensation to prevent the inequality of load on the motor due to the position of the car. The simplest form of compensation consists of wire cables of the same number and size as the hoisting cables connected to the bottoms of the car and the counterweight and passing over idling sheaves in the pit. Chains are often used in place of cables for cable compensation.

CONCLUSIONS

The desirable features are safe, smooth and quiet operation, ability to lift the required loads, no heating above Underwriters requirements, continuity of service, low maintenance costs and low power consumption. To obtain the lowest possible maintenance cost and power consumption, the first cost must necessarily be relatively high, so it is important to consider the frequency of duty demand in order to determine which to sacrifice in making an installation.

III.—THE ELEVATOR MOTOR

POWER REQUIRED

In the application of the electric motor to elevator service, it is first necessary to determine what power is required to drive the elevator. This depends upon the net load to be lifted, the car speed and the various friction losses.

The static friction is unavoidably great, it being necessary in some cases to apply two and one-half times full-load running torque in order to start hoisting the fully loaded car.

The following formula will give the horse power required at full speed with full load on the car. The motor losses are included in this formula. Therefore h. p. = the horse power input to the motor. To get the horse power motor rating multiply h. p. by the motor efficiency.

$$\text{h. p.} = \frac{L \times S}{33{,}000 \times E}$$

where L = Net load in pounds.
S = Full speed of elevator in ft. per min.
E = Overall efficiency.

The line to load, or overall running efficiency of an elevator varies from about 40 to about 75 per cent, depending upon the type, design and construction of the motor, controller, machine, guides, etc. (See "Counterweighting" above).

If the efficiency is known, the above formula may be depended upon to accurately give the horse power rating of the motor for operating the car at full speed with full load. On direct current where, within reason, the available starting torque is a function of the inrush current the size of motor derived from the formula can be depended upon to start the load from rest.

On the other hand, the available starting torque of alternating-current motors is a question of inherent design, and all motor builders do not build their a-c. motors for the same percentage of full-load torque for starting, so it is desirable that these motors be checked on a torque as well as on a horse power basis.

The difference in treating this matter of torque and horse power by different manufacturers of motors has proved confusing. It is therefore of interest to know that the Electric Power Club has taken the subject in hand and is now working out standard ratings which it is hoped all motor manufacturers will adopt.

If a specific installation has an overall running efficiency of 50 per cent and it requires two and a half times full-load running torque of the motor in order to start the maximum rated load in the hoisting direction, the starting efficiency will be only 20 per cent.

After any gear-driven machine starts there is usually a decided increase in efficiency of the gearing owing to the oil film which rotation effects between the gears. Also on all types of elevator machines the efficiency increases after starting due to the oil film which rotation automatically places between the bearings. Therefore, immediately after starting there is an excess of torque which becomes available for acceleration. The amount of this torque depends first, upon the excess motor torque that is provided over and above that actually required to start the machine in motion, and second, upon the excess in elevator starting efficiency over and above the assumed 20 per cent.

In the following formula for the determination of torque required to start an elevator, the starting efficiency has been assumed at 20 per cent as outlined above. If this efficiency in any case is lower, the elevator will not start with the torque as derived by the formula. If the efficiency is greater and allowance is not made in the formula, the derived torque may be so great that the start will be abrupt unless some control arrangement, external to the motor, is included to reduce the initial torque.

$$T = \frac{5252 \times L \times S \times 2\tfrac{1}{2}}{33{,}000 \times 0.5 \times \text{r. p. m.}}$$

$$T = \frac{0.8 \times L \times S}{\text{r. p. m.}}$$

where T = Torque in pounds at one foot radius on the motor shaft.
L = Net load in pounds.
S = Full speed of elevator in ft. per min.
r. p. m. = Full-load speed of motor selected.

Really, instead of using the formula it would be better to actually test the pounds of torque required. Obviously this is not often possible.

GENERAL MOTOR CHARACTERISTICS

Elevator motors should have the following characteristics:

1. Good speed regulation under varying load conditions.
2. High starting torque.
3. Relatively low inertia.
4. Quiet operation.
5. Adequate thermal capacity.

An elevator load varies from full positive or even 10 to 25 per cent positive overload to a negative or overhauling load. Good speed regulation is therefore an important consideration. A good many elevators are sold on the basis that they will develop a certain speed with a given load but that they will be capable of lifting a heavier load at a somewhat reduced speed. It is very important that the speed should not increase materially over rated speed in lowering a heavy load. If an elevator is operating at 600 ft. per min. under normal load conditions and it should lower the maximum load at full speed much in excess of this, it might trip the car safety guide grips.

The necessity for a high starting torque has already been outlined.

Because of frequent starts and stops and the necessity for a quick "get away" and rapid slow-down at landings, the inertia of the revolving armature or rotor should not be excessive. This means a relatively small diameter armature with not too much weight in its makeup, and revolving at reasonable speed. For passenger service about 900 rev. per min. is the usual maximum, although no definite limitation can be made, as there are successful elevator installations where the motors run as high as 1800 rev. per min. These however are usually the smaller, low-speed elevators.

While increased flywheel capacity of the revolving armature or rotor undoubtedly increases the power consumption, and therefore is objectionable, on the other hand, it is of advantage in preventing sudden variations in speed of the elevator car. A large flywheel capacity in the rotor of an elevator motor makes it difficult to obtain a rapid variation in acceleration or retardation and therefore makes for greater comfort to the passengers. It is best to strike a happy medium between comfort, speed of acceleration and operating efficiency.

Quiet motor operation is essential on practically all passenger installations and on many freight jobs also.

Because of the extreme differences in service and the great variety of load conditions encountered in electric elevators, it is impossible to establish any standard duty cycles for this service. It has been found that motors designed for a 15- or 30-minute intermittent rating will take care of most installations. A 15- or 30-minute rating means that the motor will carry its specified load for the specified period of time, starting cold, without exceeding the guaranteed temperature rise.

DIRECT-CURRENT MOTORS

Most direct-current motors, whether shunt or compound wound have suitable commutating pole windings so as to insure sparkless commutation in both directions of rotation. The commutation should be such that with heavy momentary overloads at starting and during dynamic braking, the commutator will remain in satisfactory operating condition without need for frequent attention.

Direct-current motors are of two general types, single-speed and adjustable-speed, the latter having speed control by shunt field variation. For low-speed, heavy-duty service the motor is usually compound wound to produce sufficient starting torque. The compound winding should represent from 10 to 25 per cent of the total ampere turns on the main poles of the motor, *i. e.*, disregarding the commutating pole windings. The compound winding should be cut out of circuit after starting so as to insure more constant speed characteristics. To reduce the speed to insure accurate stopping, it is necessary to insert resistors both in series and in parallel with the armature. This means inefficient starting and stopping and increases the power consumption materially, as the number of stops per car mile increases. The parallel resistor is also used to secure dynamic braking in the off position.

The adjustable-speed, shunt-wound motor, usually having a speed range of two-to-one or more by shunt field control, provides ample starting torque without a compound winding. For high-speed installations, if this type of motor is used, the elevator can be run at full field speed practically as efficiently as at high speed. In transferring from high to full field speed the motor acts as a generator and returns current to the line. The amount of this returned current has been found from actual test of a three-to-one motor to equal 10 per cent of the total power consumption on an elevator making 150 stops per car mile. For slowing down from full-field to "drag" speed, series-parallel resistor connections are used, but the horse power is only a fraction of that at high speed, so that a saving of power at drag speed is realized over power used in slowing down a single-speed motor. Should anything happen to the armature shunt contactor or to the armature shunt resistor circuit the operator can always slow down to full field speed and make a safe stop without dynamic braking. One thing against the two-speed motor is that for the same horse power and speed it must be somewhat larger and more expensive than a single-speed motor. It is highly important that the two-speed motor be designed to provide stable speed conditions when running with a weakened field.

ALTERNATING-CURRENT MOTORS

These are of two general types of a-c. motors, the high-torque squirrel-cage induction motor and the slip-ring, wound-rotor induction motor. The squirrel cage motor is used extensively up to about 20 h. p. because of its simplicity and because it only requires a relatively simple form of controller as it is generally thrown across the line with no starting resistor. When the installation is such as to require a smooth start, a resistor or reactance is placed in the motor primary circuit and gradually cut out after starting.

The last method of starting has been applied to motors as large as 50 h. p. with success. However, it has one disadvantage in that its speed regulation is poorer than that of a wound-rotor motor. While this is of little moment for the lower-speed elevators, it may not be satisfactory on the higher-speed cars. It is of interest to note that this regulation is not as bad as that of a hydraulic or a steam elevator. In actual service the power consumption of the squirrel-cage motor is slightly higher than that of the slip-ring machine, but due to the lack of slip-rings and fewer controller parts it is somewhat more reliable. The slip-ring motor for the same rating is more expensive and has a somewhat lower power factor than the squirrel cage motor.

The slip-ring wound-rotor motor is a standard product and has been used practically as long as electric elevators have had alternating-current drive. It has a higher full-speed running efficiency because the resistor in the rotor circuit is cut out by the controller after the motor starts. Its disadvantages have already been outlined.

Single-speed alternating-current motors cannot ordinarily be applied to elevators running faster than 200 ft. per min. because no slow-down can be obtained under the varying load conditions met with in elevator service, and no dynamic braking is available to assist the mechanical brake in bringing the elevator to rest. This means therefore, that the mechanical brake must be depended upon satisfactorily to stop the car from the full running speed. This is a difficult problem. The energy stored in the moving mass is proportional to the square of the velocity. The mechanical brake is capable of absorbing this energy only in direct proportion to the velocity, while a dynamic brake will dissipate this energy in proportion to the square of the velocity. The dynamic brake, unavailable with alternating current, is an important adjunct in assisting the mechanical brake for quick, smooth stopping of the elevator. While the development of the two-speed alternating current elevator motor is still in its infancy the demand is so great that rapid perfection of this type of motor for passenger elevator needs is to be reasonably expected. Alternating-current motors are very reliable, and alternating current is daily coming into wider commercial use, so it is quite essential that drastic efforts be exerted along these lines.

The available two-speed alternating-current motors today generally have two primary windings, although some motors are manufactured with but one primary winding which is re-connected to give a range in speed control.

In the two-winding type of motor the connections are usually so arranged that the speed of the motor can be changed without disconnecting the motor from the supply circuit, so that the motor is at all times operating under a positive torque and there is therefore no danger of losing control of the load.

Two-speed a-c. motors are built in both the squirrel-cage and wound-rotor types. The wound-rotor, two-speed motors have two secondary windings. Most of them have five slip rings so as to get the advantage of independent accelerating adjustments for the two windings. There seems to be a tendency toward the straight two-primary winding, squirrel-cage motor which is simpler and which has been found to give even smoother and quieter operation than the other type. Most two-speed motors have three-to-one speed range. Advantage is taken of the fact that in changing connections from the high- to the low-speed windings, with the car running at full speed, the low-speed winding acts as an induction generator, giving a very powerful slow-down action. This change is somewhat difficult to control smoothly under varying load conditions.

Some manufacturers, in order to get positive speed control with alternating current are using two motors of different rated speeds, both of which are direct connected to the elevator machine. This scheme permits the use of a squirrel cage motor for the low-speed member and a slip-ring motor for the high-speed member. With this arrangement it is possible to obtain the advantages of lower slip and higher operating efficiency which are characteristic of the slip-ring motor. Another point in favor of the two-motor arrangement is that the windings are in the usual form with which all repairmen are familiar and therefore the chances are that quicker repairs can be made. Also equipments have been built consisting of two distinct motors, both in one motor frame.

The two-speed alternating-current motor is being successfully used with car speeds as high as 350 ft. per min. Further development will undoubtedly increase this maximum.

IV—ELEVATOR CONTROLLERS

The elevator controller is one of the most important and at the same time perhaps the most complicated part of the equipment as it provides many of the safety features. The smooth operation of the elevator car is largely dependent upon its functioning, and the design affects the power consumption to a marked degree. Considerable economy can be obtained by selecting the best type for each particular application.

CHARACTERISTICS

Among the more important characteristics of the control are safety and reliability, although the motor selected should have characteristics that render it inherently safe for elevator operation. The connections to the controller must permit stopping the car at any time under any conditions of load; it should automatically stop upon the release of the car switch handle by the operator. The elevator car must be stopped automatically at each limit of travel to prevent it from traveling into the pit at the bottom or sheave beams at the top of the hoistway. The question of safety is associated with that of reliability. Even if the scheme of control is essentially safe, its proper functioning depends upon the apparatus being reliable.

Controllers must be designed and built to withstand frequent severe operation; one half a million operations a year, partly at least with inexperienced operators who do a great deal of "inching" for landings, not being unusual. Frequent plugging is common, with resultant high currents to be commutated. Also the location of elevator machinery is not conducive to regular inspection, and frequently maintenance is left to the janitor of a building who ordinarily knows little about electrical apparatus and its care.

Elevators are installed in buildings for the purpose of carrying passengers between the ground floor and the upper floors. Many buildings are so tall that it would be a distinct hardship and often an impossibility for the tenants to walk up and down stairs. It is, therefore, necessary to have the elevators in operating condition at all times. In the event of fire or accident it is important that they should function properly to remove the tenants from the upper floors of the building.

Frequently the elevator equipment is located above the hoistway or adjacent to it, so that it is essential to have the controller quiet; otherwise it may disturb the persons who occupy the upper floors.

All unnecessary complications should be eliminated from the controller and all essential adjustments should be readily understood and easily made. After being adjusted the parts should remain fixed under normal operating conditions.

The controller should be neat in appearance and all working parts readily accessible for inspection and repairs. It should be so located as to provide ample working space around it, and sufficient illumination should be provided to facilitate inspecting and repairing this apparatus.

FUNCTIONS

The elevator controller performs a number of different functions, among the most important of which are the following:

To start the motor and accelerate it to full speed in either the up or the down direction, and to stop it at the will of the operator.

The starting and the stopping of the motor is performed by switches which must make and break the electric circuit. These switches are subject to considerable burning and should be of such design as to withstand this action with infrequent repairs and renewal of parts. The smooth acceleration and retardation of the motor are most important, and usually present the greatest difficulties in the design of the controller. Under different conditions of loading, the motor may act either as a motor or as a generator; therefore the usual methods of accelerating and retarding with a positive load may not give smooth operation when the load is negative. For example; when resistance is inserted in the armature circuit of a d-c. motor under a positive load, the speed of the motor decreases in proportion to the resistance which is inserted. If, on the other hand the motor has a negative load and is operating as a generator, the more resistance inserted in the armature circuit, the faster will be the motor speed. It can be readily seen, therefore, that the ordinary methods of control are not suitable for elevator service. The same remarks apply to a slip-ring induction motor with resistors in the secondary circuit.

To control the speed of the motor at the will of the operator.

The various methods of speed control will be discussed under a separate heading. It is necessary for the control to provide for one or more reduced operating speeds in order to make a satisfactory landing, particularly where the car speed is high. These low speeds should be positive so that they are available when the motor is operating as a generator as well as under positive load.

To stop the elevator at each limit of travel.

The elevator car travels in a hoistway which is limited at the bottom by a pit and at the top by the beams which support the sheaves and often the winding machinery.

Low-speed elevators can be readily stopped at the top and bottom landings without a preliminary slow-down device, but the higher-speed passenger elevators must be slowed down before the terminal landings are reached in order to make a successful stop. This can be better understood if we consider that the car may be approaching the bottom landing in one case with no-load and in the other case with the maximum load. If the car operates at a speed of 400 or 500 ft. per min. the loaded car will drift considerably farther than the empty car when the controller disconnects the motor from the line and applies the brake. The terminal stops must be so adjusted that the car will reach the bottom landing with a light load. It will, therefore, drift considerably beyond this landing with the maximum load. If the controller provides means for reducing the speed of the car to 50 or 100 ft. per min. before the final stop is made the difference in drift between no-load and full-load will be very small and a satisfactory stop can be made.

To provide additional means for disconnecting the motor from the line and applying the brake in case of overtravel.

The car is stopped at either limit of travel by the regular slow-down and stopping device, but should this device become inoperative, additional means are provided for positively disconnecting the motor from the line and applying the brake in case the car travels beyond its ordinary limits. This latter means usually consists of hoistway limit switches so arranged that the car will open them and stop if it travels beyond its usual limits.

To provide a brake which will positively stop the car and hold it securely at the landing.

Two forms of brakes are used. One is a mechanical brake which is applied by a spring and released by a magnet. This brake is set when the magnet coil is disconnected; it is used for making the final stop and holding the load. The other is the dynamic brake which is used on direct-current machines to assist the magnet brake in stopping the machine. This is obtained by connecting the terminals of a d-c. motor to a resistor, the moving load driving the motor as a generator. By changing the resistance in the armature circuit the retarding torque can be adjusted to suit existing conditions. The satisfactory stopping of the car depends upon the proper adjustment of these two methods of braking.

The controller should govern the motor in an economical manner. The degree of economy will differ for each type of equipment. The current which passes through the resistor units represents a direct loss of energy; therefore the longer this resistance is in circuit, and the more current that passes through it, the less the efficiency of the elevator.

METHODS OF OPERATION

A controller may be operated in several ways:

Hand Rope and Lever Control. This consists of a rope which runs the full length of the hoistway in the form of a loop. (Fig. 7 shows the electrical equipment). One half of this loop passes through the elevator car. While the car is in operation this rope is stationary. In order to start, the operator pulls on the rope. This moves the controller and connects the motor to the line for the proper direction of rotation. When the desired landing is reached the operator takes hold of the rope so that the movement of the car pulls the rope in the opposite direction and brings the car to rest. This method of operating elevators is used for low-speed freight machines. A lever or hand-wheel may be used for manipulating this rope instead of having the operator pull on the rope directly. Attachments of this kind enable the operator to govern the controller at higher car speeds, but they are rather cumbersome and not as desirable as full electric control.

Car Switch Control. This method consists of locating a master switch in the car. (Figs. 8 and 9 show typical control panels.) The movement of the master switch handle to either side causes the car to travel in the direction desired. The connections are usually made so that the movement of the handle toward the door or front of the car causes a downward motion and a movement in the reverse direction an upward motion. The switch is arranged with a spring for centering the handle in case the operator releases it, thus bringing the car to rest. The handle is provided with a latch for holding it firmly in the "off" position to prevent accidental starting of the car.

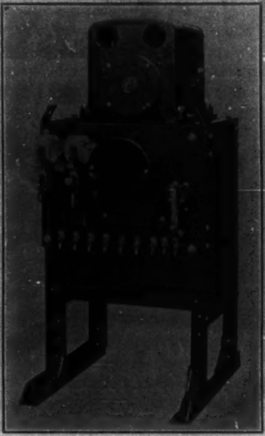

FIG. 7—SELF-CONTAINED A-C. SEMI-MAGNET ELEVATOR CONTROLLER

With phase failure, phase reversal and low-voltage protection.

This master switch is connected by wires with contactors on the control panel and operates the elevator by energizing the magnets of these contactors. The acceleration of the car is automatic so that the car switch is used only to determine the direction of travel and to select the proper operating speed.

Push Button Control. This method of controlling the car provides for automatically stopping it at the desired landing. (Fig. 10 shows a typical control panel.) It has a particular field of application in apartment houses, small hotels, stores, clubs, etc. where the service does not warrant the expense of a regular operator. The control itself is inherently more complicated than other types and therefore is not quite as reliable. It is a time and power waster because so many trips are made with light loads and without regard to floor demands.

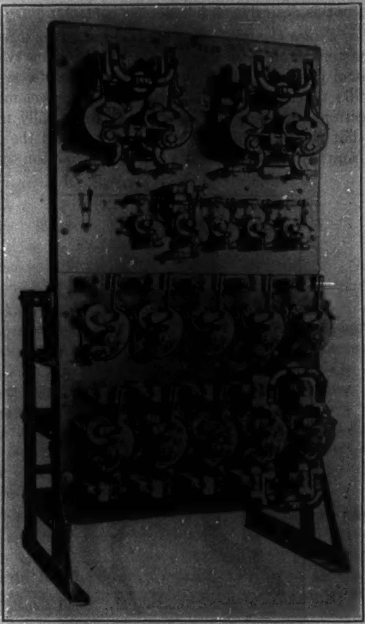

Fig. 8—Full-Magnet D-C. Elevator Controller

A push button is located near each landing door. When a button is depressed momentarily, the proper connections are set up in the controller to move the car to that particular landing and to automatically stop it when it reaches the landing. Inside the car is located a series of buttons, one button corresponding to each landing. When the passenger enters the car and closes the landing door and car gate he momentarily presses the button corresponding to the desired landing. The car then travels to that landing and automatically stops. The control for elevators of this kind is substantially the same as for an elevator using a car switch, with the addition that a selector switch is provided which is driven either by the machine or by the elevator car and makes the connections that automatically stop the car at the desired landing. One form of selector is shown in Fig. 11.

Dual Control. Dual, or combination, car switch and push button control fills a demand where the service justifies the employment of an operator for only part of the time that the elevator must be in service. This demand comes in larger apartment houses, industrial office buildings, clubs, etc. Its first cost is higher than that of any other type, but due to the two different forms of control is somewhat more reliable than the straight push button control. Push buttons are provided at each landing for calling the car to that landing. A set of push buttons and a master switch is placed inside the car. Means are provided to render the push buttons within the car inoperative when the car switch is being used. At the same time the connections to the landing push buttons are transferred to the annunciator operation.

Fig. 9—D-C. Gearless Traction Elevator Controller

Method of Acceleration

The elevator motor is automatically accelerated from rest to the operating speed. There are several methods for obtaining this automatic acceleration. Among the more common methods are the following:

Time Element Acceleration. This is based on the principle that time is required to accelerate the motor. Usually the device provides a definite time for acceleration independent of the load of the car. One of the most common devices of this type is a dash-pot, either air or oil.

The advantage of this method of acceleration is the smooth start which it provides under all conditions of loading. Sufficient resistance can be provided to start the car smoothly with a light load. With a heavy load the timing device short-circuits sections of resistance until the motor develops sufficient torque to accelerate the load. Well designed accelerators of this type are not materially affected by variations in line voltage.

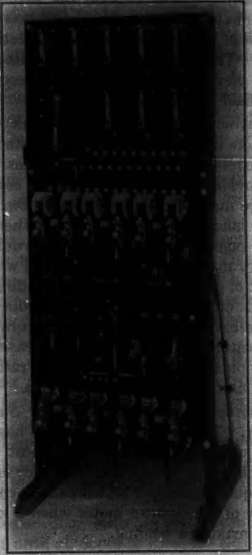

Fig. 10—A-C. Full-Magnet Elevator Controller
With floor selector relays for push-button operation.

Counter E. M. F. Acceleration. This method makes use of the principle that the voltage across the terminals of the elevator motor increases with the speed of the motor so that magnet contactors connected across these terminals have their magnetism increased with the speed of the motor and can be adjusted to short-circuit sections of the starting resistance corresponding to different motor speeds. These magnetic contactors when properly designed are not affected seriously by atmospheric conditions, dust, or dirt, and therefore should remain in adjustment. This method of acceleration is sensitive to a variation in line voltage, but elevators are usually connected to the same service lines that furnish the lighting for the building and the voltage regulation is generally very good. Where poor regulation exists, special devices can be used to compensate for voltage fluctuation. The starting resistor should permit the motor to develop sufficient torque to start the maximum load.

Current-Limit Acceleration. This method of acceleration is dependent upon the current taken by the motor during acceleration. The motor must draw sufficient inrush current from the line to develop the torque necessary to start hoisting the maximum load. After this load has been started from rest the friction decreases as the running friction is less than the static friction; therefore, a larger part of the motor torque is available to accelerate the load, and the motor increases in speed until the torque developed is just sufficient to balance the load. At this value of current a relay closes the contacts to the next accelerating switch which in turn accelerates the motor to a higher balance speed. This process is repeated until all of the starting resistance has been short-circuited. With this method of control the motor is accelerated at a constant torque value, and therefore it reaches full speed quicker with a light load than with a heavy load as more torque is available for acceleration.

All magnetic contactors require an appreciable time to close so that any control system using contactors will have some time element. By modifying the design of these contactors the time element can be increased. This small time element is useful when the counter e. m. f. or current-limit method of acceleration is used to assist in giving a smooth start.

Another element which contributes towards smooth operation is the induction in the motor circuit. This inductive action checks the rush of current at the time a contactor short-circuits a section of armature resistance. The inductive effect may be increased by adding an impedance coil to the circuit or by a special design of the elevator motor itself. The time constant of the motor may be increased by several well known methods, thus smoothing out the transition between the steps in the controller.

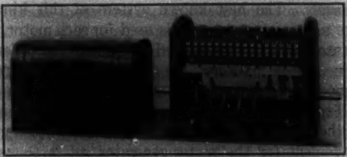

Fig. 11—Elevator Floor Selector

An elevator motor may be accelerated by a combination of two or more of these methods. As pointed out above, there is always some time element in every contactor, which may be increased by special design, this giving a combination of *time element* acceleration with either *counter e. m. f.* or *current-limit* acceleration.

V. Methods of Speed Control. The speed control of the elevator motor is very closely associated with the method of acceleration and may assist materially in smoothing out this acceleration. The method of speed control depends upon the type and design of motor. Some of the methods are as follows:

By Adjusting the Field Strength of the D-C. Motor. Most direct-current motors can be operated at different speeds by simply changing the strength of their fields. The range of speed obtained depends upon the design of the motor. If a considerable change in speed is required by this method, a larger and more expensive motor is required than for the ordinary constant-speed design. If the motor is massive and responds slowly to a change in field strength, very little difficulty is introduced by this method of speed control. If, however, the motor responds quickly, relays or other devices are used to limit the current during the change in speed. This method of speed control is very popular, particularly for the higher-speed, geared elevators. This is a very economical method of speed control.

By Connecting Resistors in Series and in Shunt with a D-C. Motor Armature. The shunt resistor has a stabilizing influence and limits the speed variation under different conditions of loading. This method of control is very commonly used to obtain the low speed from which a landing is made. With the same amount of resistance the speed will vary considerably, depending upon whether the motor has a positive or negative load, but for making a landing this speed range is not too great to obtain practical results. It is the least economical method of speed control of a d-c. motor and is therefore, generally used only for obtaining the landing speeds.

By Applying a Variable Voltage to D-C. Motor Terminals. The best known system of this kind is where a separate generator is used for each motor, the generator field being changed to obtain the different motor speeds. Where the generator is properly designed the elevator motor can be operated from rest to full speed in either direction by changing the strength and the direction of the generator field. A good arrangement for the motor-generator set is to use a single motor driving two generators in order that the elevators may be shut down in pairs to eliminate the standby losses.

By Applying Several Different Voltages to the Terminals of a D-C. Motor. These different voltages are usually obtained from a motor-generator set having several different generators, each generator providing a different voltage. The transition between voltages is obtained by inserting resistance in the armature circuit. With this method of control it is necessary to reverse the armature connection to reverse its direction of rotation. One motor generator set usually supplies several elevators.

Where a storage battery is available the intermediate values of voltage may be obtained by taps taken from this battery.

The last two methods of control have been used to a limited extent. These increase the first cost of the installation but may reduce the cost of power by eliminating most of the rheostatic loss during acceleration and slowdown. This is of particular advantage in cases where the elevator motor has little speed regulation by shunt field control.

By Changing the Number of Poles of an A-C. Motor. These motors are of the induction type and may have either squirrel-cage or wound secondaries. They are usually provided for two different pole combinations; one, a large number of poles giving a low speed from which the landing is made and the other a smaller number of poles providing the regular running speed. The primary may have either two sets of windings, one for each set of poles, or a single set of windings arranged for two sets of connections. The introduction of the two-speed a-c. motor has enabled the operating speeds of a-c. elevators to be materially increased. One of the most popular combinations is a 3 to 1 ratio, although motors are now built with a 6 to 1 ratio.

By Changing the Frequency of Power Supply to an A-C. Motor. This method of control has been very little used up to the present. The most convenient method of obtaining the reduced frequency is to provide a small frequency changer which can be connected to the primary of the elevator motor when a low speed is desired for making a landing.

DETAILS

The elevator controller is made up of a number of unit parts, each of which performs a function in controlling the elevator. The parts usually found in a controller together with their functions are as follows:

1. A line switch for disconnecting one side of the motor from the line. This switch may be operated every time the car is moved or it may remain normally closed and be opened by a safety device or by failure of line voltage.

2. Reversing switches which change the direction of rotation of the motor and are normally used for opening and closing the motor circuit. Some of these switches operate each time the car is moved. For magnet control either two double-pole or four single-pole switches are used.

3. The accelerating device which automatically short-circuits the starting resistance when the motor is being brought from rest to the operating speed. A similar device may be used to limit the armature current when the field strength is changing.

4. A dynamic brake for slowing down the d-c. motor when the elevator is brought to rest. This brake consists of an electric connection between the motor terminals and a set of resistors. The switches for making these connections may form part of the reversing switches or may be separate units, the number depending upon the car speed and the type of motor.

5. A mechanical brake for making the final stop and holding the car securely at the landing. This brake is usually applied by a spring and released by a magnet.

6. Terminal stops for bringing the car gradually to rest at either limit of travel independently of the operator. Usually two different devices are used for this purpose, one of which operates normally and the other an emergency device as previously explained. The second set is generally known as *overtravel limit switches*.

7. Some means in the elevator car which will enable the operator to control the elevator. This may consist of a rope or a lever, a car switch or a set of push buttons depending upon the method of control.

8. A safety switch in the car for stopping in case of failure of the regular operating means.

9. A slack cable device for stopping the motor in case the car or counterweight is obstructed in its travel. A device of this kind is required only for drum machines.

10. High-speed elevators usually have a switch operated by the speed governor which automatically reduces the motor speed if it exceeds a predetermined limit.

11. Gate or door switches to prevent operating the elevator until all doors or gates are closed.

12. Every controller should provide overload protection. This may consist of fuses, but is usually a circuit breaker, or an overload relay operating in conjunction with the main line contactors.

13. Where the operating device in the car is not self-centering, low-voltage protection should be provided, to prevent the accidental starting of the elevator after failure of power until the operating mechanism has been returned to the "off" position. For a-c. elevators this device usually protects against the failure of power in any phase of the supply circuit.

14. Alternating current motors should have protection against an accidental reversal of phase which would cause them to operate in the wrong direction.

15. The higher-speed elevator controllers provide for a low-speed for making a landing. Sometimes the control provides for several operating speeds less than the maximum running speed.

16. A floor leveling device is sometimes included as part of the control. This consists of automatic means for bringing the car platform level with the landing and maintaining it in this position.

Each type of elevator requires its own special form of control. The lower-speed machines require a less complicated control than when the elevator is operated at a higher speed. Often freight elevators have different requirements from passenger machines. Considerable skill and experience is required in the designing of control equipment and selecting the necessary features. Each control should contain all of the features necessary for a successful operation, but any additional features add to the complication and may be undesirable.

V—BRAKES AND OTHER SAFETY ACCESSORIES

Brakes and other safety accessories have little to do with power application to electric elevators but they are so vitally a part of the elevator equipment that a good idea of the complete elevator plant cannot be obtained without a complete understanding of these features.

BRAKES

While the brake is a small part of an elevator machine it is an exceedingly important part. Because of the frequency of starts and stops it is highly essential that the car be brought to rest quickly and without shock or jar to the passengers. Also once brought to rest it is just as important that the car be maintained in its position in the hoistway while passengers are leaving and entering it. The functions of bringing the car to rest and maintaining it in a stationary position are obtained by the brakes. Elevator brakes are divided into three classes,—mechanical, dynamic and magnetic.

Mechanical Brakes. The straight mechanical brake is little used. To some extent it is still being installed on hand rope controlled freight elevators and sidewalk lifts. Most states prohibit its use on any passenger elevators because of its lack of protection to the car and occupants. As the name implies, it is simply lined brake shoes bearing against a pulley on the motor shaft. It is applied manually with the hand rope within the car, and automatically at the terminal landings by the traveling nut mechanism on the machine which has the double duty of returning the reversing switch to neutral, interrupting the motor circuit; and applying the mechanical brake. If, during operation, the voltage fails, the brake will not be automatically applied.

The mechanical brakes gives smooth results in stopping because a gradual application may easily be made by properly manipulating the control rope.

Dynamic Brakes. In the application of dynamic braking, advantage is taken of the ease with which a direct-current motor may be converted into a direct-current generator. The shunt field either partially or fully energized is connected to the line, and the revolving armature is shunted with a resistor. Thus the motor operates as a generator and "pumps" current through the dynamic braking resistor thereby converting the mechanical energy of rotation into electrical heat. While this type of brake alone will not bring an elevator to rest, particularly if the load is overhauling, it will materially reduce the speed so that from that speed the magnetically operated brake may easily be depended upon to bring the car to a safe and smooth stop. On the higher-speed d-c. elevators a graduated dynamic braking is furnished, which provides a braking more nearly proportional to load and speed conditions.

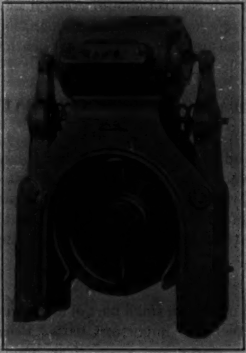
Fig. 12—D-C. Magnet-Operated Elevator Brake

With alternating current, a braking effect similar to direct-current dynamic braking is sometimes furnished when a two-speed motor is used. In this case the low-speed winding is connected to the supply lines while the armature is rotating above the synchronous speed of this winding. Thus the motor acts as a self-excited induction generator and a powerful "dynamic" braking is obtained to bring the motor down to the synchronous speed of the low-speed winding. In this case energy is restored to the line during the braking period.

Direct-current dynamic braking is wasteful of electrical energy because the energy of rotation is lost in heat. The same applies to the mechanical brake where the energy is absorbed in the brake shoes. No effective method, economical of electrical energy, has been devised for quickly slowing down and stopping an elevator, although a direct-current motor with a wide speed range by shunt field control is economical in slowing down, as is also the two-speed alternating-current motor referred to in the preceding paragraph. (See Part III.)

Magnet Brakes. The importance of the magnet brake particularly on alternating current cannot be over emphasized. See Figs. 12 and 13. The reasons for its great importance have been outlined in Part III under the subject of "The Elevator Motor."

The magnet brake consists of brake shoes, similar to those used with the mechanical brake, operated by an electromagnet. This type of brake should always be used in addition to any other, except for low-speed freight sevice, for the purpose of positively holding the car stationary at the will of the operator.

On direct current, the magnet brake has been a small problem, but on alternating current it becomes a difficult one because of difficulties in satisfactory magnet design. Various types of magnets are being used, such as single-phase long-stroke, polyphase long-stroke, polyphase short-stroke and constant-stroke. The constant-stroke magnet is no more than a small motor designed to remain across the line with the rotor stalled. This magnet is sometimes called a *torque motor*. This type of magnet does not seal. It is difficult to keep quiet an alternating-current magnet that does seal. It is liable to slam in closure, and unless the laminated parts are perfectly surfaced and perfectly aligned it will hum after closure. A dash-pot is sometimes used for long-stroke magnets to reduce the slap in closing, and sometimes the entire magnet is immersed in oil to deaden the noise. One type of constant-air gap magnet, which is very quiet, absorbs the energy of rotation in a small auxiliary mechanical brake.

It is realized that if a mechanical brake action could be accomplished automatically in a magnet brake, smoother stopping results on alternating current could be obtained. Three manufacturers have tried the following schemes: A single magnet with the main brake spring partially counteracted by a weaker spring is used, and a dashpot is so arranged that the brake shoes are applied with partial pressure which quickly in-

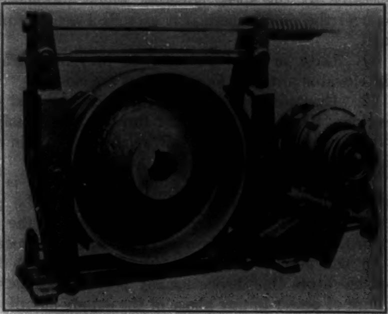
Fig. 13—A-C. Elevator Brake with Constant Air-Gap Magnet

creases to maximum. The main objections to this are the use of a dashpot and the fact that the operator does not have any control over the weak and strong settings. Another scheme is the use of two independent magnets or complete brakes, in which case the operator has control over the weak and strong settings, giving good stopping results. The objection to this is the use of two magnets. The third method consists in the use of a single short-stroke polyphase magnet with a variable reactance in the magnet circuit proportioned to break the seal of the magnet but still maintain sufficient current in the brake coils to partially counteract the brake spring tension. As the car control switch is moved towards the "off" position, this reactance is decreased so the action of a mechanical brake is practically reproduced. This has worked out sufficiently well so that it is being used on elevators driven by single-speed motors and running 300 ft. per min. An objection to this method is the noise which is always present to some extent when the reactance is cut into circuit.

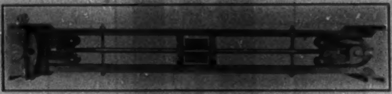

FIG. 14—ELEVATOR SAFETY GUIDE GRIPS

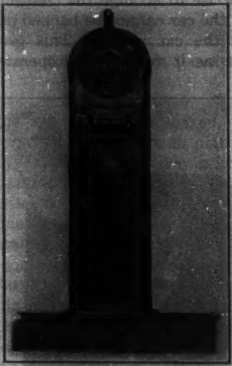

FIG. 15—ELEVATOR CAR OPERATING SWITCH

The last two types must be so wired that there will be no way for the operator to hold the weak brake condition when the car is close to the terminal landings.

As a safety measure all magnetically operated brakes are so designed that the brake is released by the magnet and applied by springs or weights, so that a failure of power will always stop the elevator.

SAFETY DEVICES

These may be classified as electrical and mechanical. The mechanical are so closely allied to the electrical that they will be briefly described. The principal safety devices are, guide grips and overspeed governor with governor switch, car-operating switch, car safety switch, terminal-limit switches, overtravel-limit switches slack-cable switch, door switches, compensating-cable-sheave switch, buffers and air cushions.

FIG. 16—CAR SAFETY SWITCH

Guide Grips and Overspeed Governor. Guide grips have been made in a number of different types such as eccentric, dog, roller, and wedge, the wedge type now being almost universally adopted. See Fig. 14. The mechanism, is mounted below the car with a small winding drum which is connected to the overspeed governor by a steel cable. The holding of this cable at excessive car speeds rotates the drum so that the wedges force the grips against the guide rails and stop the car.

Usually a fly-ball type of governor is used in connection with the guide grips so arranged that the cable referred to rotates the governor shaft. The governor is arranged with a grip so that if the normal speed of the elevator is exceeded by a fixed amount it holds the governor cable and effects the setting of the guide grips.

FIG. 17—MACHINE LIMIT SWITCH FOR DRUM-TYPE ELEVATOR

It is accepted practise to install a control switch on the governor, so adjusted that the switch will trip to open the control circuit and disconnect power from the motor at a speed lower than the speed at which the guide grips act. This switch prevents the guide grips from setting in case of a slight overspeeding. The switch is arranged so that it cannot be reset unless the guide grips are in the running position.

Car-Operating Switch. The car-operating switch usually has the automatic return or self centering feature so that if the operator's hand is removed from the lever it will return to the off position. See Fig. 15. It also is ordinarily provided with a center latch so arranged that any accidental leaning against the switch will not move the lever to the running position.

Car Safety Switch. The car safety switch is for the purpose of stopping the car in emergency in case of the failure of the car operating switch. Fig. 16. It is wired in a separate cable of opposite polarity to the car-switch cable, so that in case of grounds, etc., in the car-switch cable, the car safety switch will not be thrown out of commission.

FIG. 18—INSTALLATION OF ELEVATOR HOISTWAY LIMIT SWITCH

Terminal Limit Switches. These act each time the car approaches the terminal landings, and function to bring the car to rest at these landings in case the operator is careless. See Figs. 17 and 18. They may be mounted on the car and operated by cams in the hoistway or vice versa for a traction-type elevator. These may also be used on a drum-type elevator although frequently limit switches geared to the elevator machine are used instead.

Overtravel-Limit Switches. Overtravel hoistway limit switches, Fig. 18, are always mounted in the hoistway and are operated by cams on the elevator car. They are placed beyond the normal range of car travel, and function to stop the car in case of the failure of the regular terminal stop limits. It is very desirable and the usual practise to arrange the connections to these limits so that the car cannot be backed out of them by manipulating the car switch. This gives an added safety feature as it requires the operator to call the attention of an electrician or someone connected with the maintenance department to the fact that the car ran into the overtravel limits, and have the cause of this overrunning corrected.

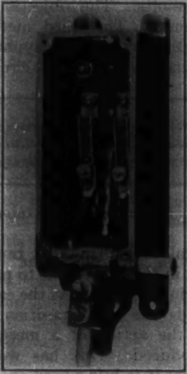

FIG. 19—SLACK-CABLE SWITCH

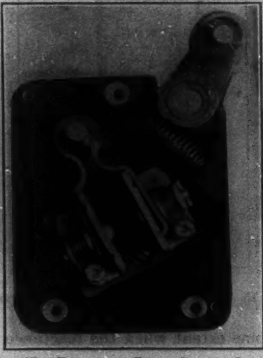

FIG. 20—ELEVATOR DOOR SAFETY SWITCH

Slack-Cable Switch. Ordinarily this is used on a drum-type elevator to open the control circuit in case of slack cable caused by the car or counter-weight being caught in the guides. It is operated automatically when the cables slacken. See Fig. 19. It is sometimes mounted on top of an elevat orcar of high travel traction elevators where the cable weight is so great that the machine may not entirely lose traction in case of the bottoming of the car.

Door Safety Switches. These, Fig. 20, in combination with door locks, prevent the car from operating unless all doors are closed and locked. The design requirements of these devices are in many cases regulated by safety codes. There are numerous types manufactured and many have little value, so that door locks and switches should be investigated before installing. Some combinations lock the car-operating switch in neutral while the door is open. Others interrupt the car-control circuit when the door is open. Because the large majority of elevator accidents are due to not using suitable door interlocks, it is advisable to use them even though it decreases the service of the elevator to some extent. (See Part I.)

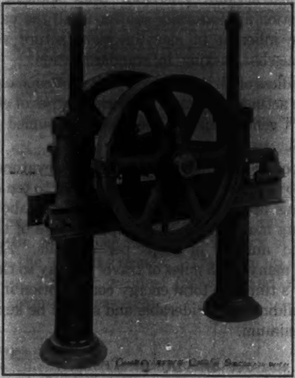

FIG. 21—ELEVATOR COMPENSATING CABLE SHEAVES WITH SWITCH

Compensating Cable Switch. This is connected so that it is opened by the lowering or raising of the compensating cable sheaves in the pit. See Fig. 21. The switch interrupts the control circuit and stops the car should the sheaves lower to any appreciable extent due to cable stretch. Also, in case of the car or its counter-weight being caught in the guides, the compensating cable sheave will raise and operate the switch to cut off power.

Buffers and Air Cushions. A buffer is always required under the car. For lower speeds a spring alone is used, but for higher speeds a combination of oil dash-pot and spring is used, Fig. 22. These must provide a retarding effect so that maximum retardation will not exceed 64.4 feet per second per second.

At one time an air cushion was required for certain service in certain localities. This consists of a hoistway practically air tight at the lower end for a certain percentage of the total height. This involved very expensive enclosure construction and while effective in retarding the motion of a falling car it is understood the air cushion has been practically abandoned as unnecessary to safety. Another disadvantage of this scheme is the additional power required to move the car due to air friction.

PROTECTIVE DEVICES

Besides the various forms of brakes and safety devices above described most elevators are protected against abuse by the following apparatus:

Main Line Service Switch and Fuses. These are mounted in an accessible location in the elevator machine room and are usually enclosed in a metal cabinet, preferably with an externally operated knife switch, and with a mechanical interlock making it necessary to open the knife switch before the cover can be opened to inspect or replace fuses.

Circuit Breakers and Overload Relays. Circuit-breaker protection of individual elevator motors is not very often used inasmuch as the National Electrical Code requires fuse protection of elevator motors even when circuit breakers are used.

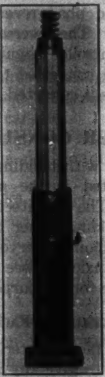

FIG. 22—ELEVATOR OIL BUFFER

Frequently, however, in addition to the service fuses, overload relays are used in order to secure protection against overloading of the elevator itself. The overload relays are set below the fuse rating so as to prevent the blowing of fuses. The overload relays are sometimes made to reset automatically with the return of the operating switch handle to neutral, so that after an overload it is unnecessary to go to the elevator machine room to again place the elevator in operating condition.

Overspeed Slow-down Relay. Some builders include in their electrical equipment a voltage relay so connected that an overspeeding of the elevator in either direction will cause the relay to act and thus automatically retard the speed. This relay is set to act at a speed below that at which the overspeed governor is set.

Phase-Failure Protective Relay. All alternating-current elevator installations on which the elevator motor may be continuously connected to the lines, such as hand-rope and push-button controlled elevators, include some form of phase-failure protection. Otherwise, upon the failure of a phase, the motor may be stalled on the single-phase condition, and burn out. The protective relay is usually a polyphase, shunt-wound relay with a control-circuit contact to maintain the control circuit of the elevator controller so long as the phases are all alive. The failure of any phase causes the relay to open the controller circuit and thus disconnect the motor from the supply lines.

Phase-Reversal Protective Relay. Many State electrical codes now require a phase-reversal protective relay on all polyphase a-c. installations. Frequently the phase-failure and phase-reversal relays are combined in one device. The reversal of phases immediately opens the controller circuit and prevents the elevator motor being connected to the lines until the relation of the phases is corrected.

VI—POWER CONSUMPTION

Anyone connected with building or industrial plant operation is interested in the power consumed by electric elevators. The architect and engineer are interested. The building owner is interested. From a conservation standpoint, everyone interested in the country's welfare is anxious to see the most economical use of electric power for all purposes.

DETERMINING FACTORS

There are so many factors entering into this problem that it is impossible to give any accurate power consumption figures for any one type of elevator with a given capacity and running at a given speed, with a specified load on the car and with a specified number of stops per mile of car travel.

The operator himself is one of the variables. Some elevator operators run their cars to good advantage from a power economy standpoint, but many others are most careless in the way they operate.

Besides the operator's effect on economy other variables are inertia (including the weights of the car, counterweights, lifting ropes, balancing ropes, or chains, all moving parts of the machine etc.), rate of acceleration, and design and construction of all parts entering into the complete elevator. To show the importance of these factors, one company may design an elevator for a capacity of five tons that will have in its make-up approximately one half the material that another company may deem advisable for the same capacity and speed. When it comes to power consumption the lighter weight apparatus will naturally win out, even though it may not last long, due to its light construction. Therefore tests showing power consumption are naturally subject to all the variations that are inherent in elevator manufacture which is still somewhat lacking in standardization.

Regardless of all these variables it is of course possible to quote actual test figures for various types of elevators so that a general idea of the power consumed may be obtained.

The power consumption of electric elevators ranges from two to three kw-hr. per car-mile up to ten or more depending upon the variables mentioned above, but depending mostly upon loads, speeds, rate of acceleration, and number of stops per car-mile. Elevators make as many as 25 miles of travel per day so that even in a day's time the total energy consumption in a large office building is considerable and should be kept down to a minimum.

RESULTS OF TESTS

Geared, Drum-Type Elevators. An average of several drum-type, geared elevators, with capacities between 2000 and 2500 pounds, at 350 to 400 ft. per min. regular service indicates the following results:

Capacity	Speed	Total miles per day	Kw-hr. per car-mile
2000	350	11.25	3.98
2500	400	10.90	4.35
2000	400	15.20	3.58
Average		12.45	3.97

Gearless Full Wrap Traction, 1 to 1 Roping. The following results were obtained from actual test of an elevator rated at 2500 lb., 500 ft. per min. with 800 lb. over-counterweight. Values are averaged for up and

Stops per car-mile	Kw. hours per car-mile	
	Balanced	Full load
0	1.20	1.82
50	2.22	3.39
75	2.90	4.07
100	3.50	4.80
125	4.10	5.46
150	4.28	5.93
200	5.12	7.10
250	5.81	9.07
300	6.50	9.20
400	7.90	11.50

down operation. The results are plotted in Fig. 23. The curves clearly show the variation in power consumption with load changes and with variation in the number of stops per car mile.

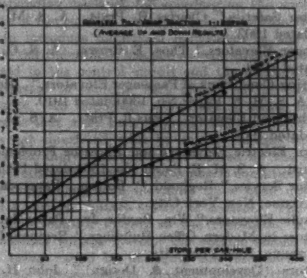

Fig. 23—Results of Test of Gearless Full-Wrap Traction Elevator, 1-1 Roping

Values averaged for up and down operation.

Another set of tests on a gearless 1 to 1 machine rated at 2500 lb., 500 ft. per min., in a ten-story office building gave the following results. These are up and down averages. The car weighed 3900 lb. and there was 1060 lb. over-counterweight.

52 Stops per car-mile							
Load in lb.	Operator	666	1060	1360	2010	2360	2660
Kw-hr. per car-mile	2.35	2.08	1.95	1.87	2.15	2.50	3.22
104 Stops per car-mile							
Load in lb.	Operator	666	1060	..	2010	..	2660
Kw-hr. per car-mile	3.09	2.86	2.52	..	2.92	..	3.86
208 Stops per car-mile							
Load in lb.	Operator	666	1060	..	2010	..	..
Kw-hr. per car-mile	4.91	4.19	3.98	..	4.25	..	..
416 Stops per car-mile							
Load in lb.	Operator	666	1060	..	2010	..	..
Kw-hr. per car-mile	7.29	6.75	6.7	..	7.43	..	..

A test was made in a fifteen story building. The elevator was rated at 2750 lb. at 500 ft. per min. The regular service test with approximately 100 stops per car mile gave an energy consumption of between 3.32 and 4.73 kw-hr. per car-mile.

The effect of increased number of stops is shown in the following results obtained from a test in a 22-story office building:

Empty —Stopping at every floor............ 6.4 kw-hr. per car-mile
Full Load —Stopping at every floor............ 10.4 " " " " "
2/3 Load —Stopping at top and bottom only.. 2.4 " " " " "
2/3 Load —Stopping at every floor............ 8.8 " " " " "

A 22-floor 600 ft. per min. elevator with express service to the tenth floor and local service from the tenth to the twenty-second floor, traveling an average of 22 miles a day consumed 3.5 kw-hr. per car-mile. Local elevators in the same building operating at 400 ft. per min. traveled nine miles per day and consumed an average of 4 kw-hr. per car-mile each.

Gearless Full-Wrap Traction Elevator 2 to 1 Roping. The only tests available for publication are shown in the following table. The elevator was rated at 3000 lb., 500 ft. per min., 1175 lb. over-counter-weight was used. Average up and down results are given:

Stops per car-mile	Kw-hr. per car-mile	
	Balanced	Full Load
0	2.00	3.80
50	2.90	4.60
75	3.40	5.40
100	3.90	6.00
125	4.33	6.95
150	4.81	7.80
200	5.80	8.71
250	6.78	10.40
300	7.68	11.10
400	9.06	15.20

Geared Half-Wrap Traction Elevator. A test was made on several elevators rated at 2500 lb., 600 ft. per min., with the following average up and down results:

Stops per car-mile	Load in lb.	Kw-hr. per car-mile
16	1100	2.06
80	"	4.20
96	"	4.70
16	2500	2.40
80	"	4.80
96	"	5.20

An elevator running 400 ft. per min. serving an 18-story building and traveling an average of 21.8 miles per day showed a regular service consumption of 3.28 kw-hr. per car-mile.

Another at the same speed in a 13-story building and traveling 19 miles a day consumed 3.88 kw-hr. per car-mile.

The average of a lot of 400 ft. per min. elevators was 3.8 kw-hr. per car-mile.

The following test results were obtained with an elevator having a capacity of 2250 lb. at 500 ft. per min. The over-counterweight was 580 lb. In this case the motor had a 3 to 1 speed variation by shunt field control. Had there been less or no control by shunt field variation the power consumption values would have been considerably higher. (See Part III.)

Stops per car-mile	Kw-hr. per car-mile	
	Balanced	Full Load
0	1.50	2.05
50	2.10	3.00
75	2.50	3.43
100	2.92	3.90
125	3.30	4.46
150	3.57	4.90
200	4.23	5.91
250	5.30	6.70
300	5.90	7.55
400	6.95	8.50

Lack of proper maintenance will also increase the power consumed. It is evident that all moving parts such as the machine itself, sheaves, guides, etc. must be properly lubricated at regular intervals in order to insure the most economical results. Also if the brakes are not properly adjusted the operators will find difficulty in making accurate stops without inching and the resultant loss in power.

CONCLUSION

While the above test figures are of interest they actually are of little comparative value on account of the many variables indicated under "Determining Factors." Some years ago the Cincinnati Gas & Electric Company made some operating cost tests on a great many elevators in its district. The averages of all these tests are given as follows:

Freight	Cost per elevator	$8.00 per month
"	" " h. p.	1.09 per month
Passenger	" " elevator	14.64 per month
"	" " h. p.	1.26 per month

These are, of course, costs for power only, and would not apply with present-day power costs.

Attention is called to the fact that the big determining factor in the cost of elevator operation lies in the number of starts and stops and not in the load carried by the car.

WAYS IN WHICH OPERATION AND MAINTENANCE AFFECT POWER CONSUMPTION

It has already been mentioned that the operator himself is one of the important factors determining the power consumption of electric elevators. It is interesting to note how this factor affects the results.

If an operator is so expert that he slows down the car as nearly as possible to the landing at which he is to stop and if he stops the car accurately with the landing without "inching" he reduces the current used in slowing down or running at low speed and reduces the number of starts and stops by eliminating the inching operation so frequently used by unskilled operators. Besides this he improves the service of the elevator which point is of vital consideration.

Evidently from the manner in which many elevators are run little attention is paid to this important factor in elevator economy. If building owners would realize the importance of this point it would be possible by careful instruction and competition between operators to materially cut down the power consumption on many installations.

Towards this end a watt-hour meter might be installed on each elevator. Also car-mile recorders and counters for registering the number of stops could be added. In this way accurate data on the performance of each elevator could be obtained. If an operator is assigned to a particular machine a bonus might be paid to the operator who showed unusual saving in power consumption due to skilful operation. In a large building this would set up a rivalry between operators and might be very beneficial from the standpoint of the power consumed.

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Discussion

H. D. James: The selection of the proper size elevator car and the proper speed of operation is very essential for the success of any installation. The tendency is to use car speeds of 500 to 600 ft. per min. on the larger installations and even higher speeds have been tried out in practise. The tendency in New York City towards very high buildings of the tower construction may lead to elevator speeds of 1000 ft. per min. or even more.

In selecting an elevator speed, consideration should be given to the distance between stops. In an ordinary office building an elevator operating at 600 ft. per min. will have to travel at least two floors to obtain full speed for even a very short part of that travel. The power consumed during acceleration is an important part of the total power consumption so that the cost of operating at 600 ft. per min. in a low rise building may be out of proportion to the benefits ordinarily obtained, unless an improved method of control is adopted.

The more rapid the rate of acceleration, the greater the advantage obtained from high-speed elevators. If the acceleration curve is the correct shape a very rapid rate of acceleration is just as comfortable as a slow rate. The human being feels the rate of change of acceleration more than the actual rate of acceleration. The correct curve can be obtained by using the second derivative of the speed-time curve. The use of the direct 1/1 traction elevator machine which eliminates all gearing is an important factor in obtaining a rapid rate of acceleration without discomfort to the passengers.

In accelerating a motor using a rheostatic controller the resistance in circuit with the armature is changed in definite steps which tends to cause abrupt changes in motor torque. One way to reduce this effect is to provide inductance in the circuit. Every electric circuit including a motor, has some inductance but this is small and a large number of controller steps are required to avoid a disagreeable acceleration. A large number of controller switches in themselves decrease the rate of acceleration as time is required for manipulating these switches. It is true that improved operation can be obtained by slowing down the operation of certain switches, but there is a corresponding necessity for speeding up the contactors in other parts of the control. A better way to obtain the desired result is to introduce additional inductance in the armature circuit. If this inductance has the correct value few contactors are required in the control circuit and the acceleration curve can be adjusted to conform very closely to the theoretically perfect curve. An important advantage in using the correct inductance is that when once adjusted the smooth operation of the car is not interfered with by minor changes in the time element of the individual contactors caused by the accumulation of dirt, change in friction, atmospheric conditions, etc.

Recent improvements in elevators have been obtained by the use of a variable voltage system of control. The older and more common control known as the rheostatic, is operated from a constant voltage system, the voltage across the motor armature being varied by changing the resistance in circuit. The variable voltage system directly changes the voltage of the generator supplying the elevator motor and no rheostatic control is required in the armature circuit. Briefly, the system consists of an individual generator for each elevator motor. The armature of the motor is connected directly to the armature of the generator and this circuit is not opened for normal operation. The direction and speed of the elevator motor is obtained by changing the direction and strength of the generator field. The only rheostatic losses are those of the field rheostat in the generator circuit.

This variable voltage system of control is inherently smooth in operation, as the field strength of the generator does not change abruptly giving the effect of an infinite number of control steps. By properly proportioning the field winding of the generator, a very high rate of acceleration may be obtained following the theoretically correct curve for acceleration and deceleration. This system of control will permit an acceleration from rest to 600 ft. per min. in very close to two seconds. It permits elevators to be operated by a-c. or d-c. power circuits as the motor-generator set can be driven by either a d-c. motor or a polyphase or single-phase a-c. motor. The a-c. driving motor may be a synchronous motor adapted for power factor correction where conditions require such an arrangement.

The power required when starting and operating at low speeds with the variable voltage system of control is less than with the rheostatic in the proportion that the generator voltage bears to the line voltage. For instance, if the generator voltage is 25 per cent of the line voltage, the elevator motor can draw approximately four times its full-load current without exceeding the full-load demands from the line. This is particularly valuable where the source of power is alternating current. Alternating-current motors during acceleration take a current equivalent to two or more times the full speed value. With the variable voltage system of control, the power demand during acceleration may be less than full load.

Where 500 or 600 ft. elevator speeds are used with the variable voltage system of control, the cars may be operated at reduced speeds with very little loss in efficiency, whereas with the rheostatic control, the power taken from the line is not reduced when the elevator speed is cut down.

In making a landing with a rheostatic controller the car speed may vary over a range of 3/1 or 4/1, depending upon the loading in the car, as the low speeds with this system of control are obtained by the use of armature series and armature shunt resistors, the voltage across the motor armature changing with the load. The variable voltage system of control can be designed to give close speed regulation at all speeds independent of the load so that the operator in approaching a landing can rely upon a definite car speed. This enables him to make his landings with greater accuracy and materially reduce the time consumed at landings. The accuracy with which low speed control can be obtained independent of the load with this system permits stops at either limit of travel to be accurately set, insuring greater safety of operation.

The magnet released friction brake used on elevator machines ordinarily functions to hold the car at the landings, the slowing down being accomplished by dynamic braking. If the friction brake is set abruptly, it causes a rough stop. In order to insure a smooth stop the tendency has been to ease up on the brake shoe so that the retarding effort of the shoe may not be much in excess of that required to actually hold the car at the landing. This is a dangerous tendency as the brake is intended as one means for emergency stopping. For that reason the brake is released by a magnet and applied by springs. If the brake is to be considered one of the safety means for stopping the car as well as holding it at the landings, the torque of this brake should be sufficient to stop within reasonable limits a fully loaded car travelling down at full speed, or an empty car traveling up at full speed. This introduces difficulties in the design of the brake as the torque required to bring the loaded car to rest within a reasonable distance may be sufficient to cause a rough stop under normal operating conditions. It is, therefore, necessary to proportion the windings of the brake so that the shoes are gradually, though quickly, applied. The best way to accomplish this is by means of magnetic induction, as a mechanical dash pot of any kind may stick fast and thereby introduce a hazard.

I would like to say a word about the high-speed geared elevator in comparison with the direct traction machine. It is well known that the efficiency of a low speed d-c. motor is inherently less than a high speed motor of the same rating, and this argument has been advanced as a reason for using a geared machine. Unquestionably there is a lower limit to the car speed which can be obtained with a direct connected 1/1 traction machine and, therefore, it is necessary to use a gearing for low speed elevators. The gearing may consist of a 2/1 rope hitch on the car giving half normal speed, or it may consist of some form of worm or spur gearing. The 2/1 rope hitch introduces additional friction losses and increases the wear on the rope. It, however, does not involve maintenance of the gearing and is an advantage from that standpoint.

All mechanical gearing has some clearance between the teeth. The high speed gearing for the steam turbine drive of ships reduces this clearance to a minimum by various mechanical expediences which, so far as the writer knows, have not been applied in the elevator field. The objection to clearances in the gearing for elevators is the lost motion when the torque is reversed. If the gearing is accurately cut and carefully adjusted, this lost motion may not be objectionable when the machine is first installed but the tendency of all gearing is to wear and wear increases the back-lash. Worm gearing requires thrust bearings to take the end thrust on the worm. The clearance required for this end thrust and for the teeth of the gearing introduces a difficult problem with high car speeds. Low speed elevators may be accelerated and decelerated at a relatively slow rate but high speed elevators require rapid acceleration in order to obtain the full advantages of high car speeds; this rapid acceleration and deceleration increases the difficulty of maintaining a geared machine in satisfactory operation.

If we assume that the overall efficiency of the high speed geared elevator can be made equivalent to the gearless machine we still have the advantage of eliminating all mechanical gearing which at best is a potential source of trouble. Where geared elevators have been installed in office buildings to operate at high car speeds, it would be interesting to know their rate of acceleration and deceleration; also how much the clearance in the gearing has increased after five or six years of service.

H. P. Reed: Mr. James suggests that the use of a gearless elevator machine is an important factor in obtaining a rapid rate of acceleration without discomfort to the passengers. It would be interesting to have Mr. James explain this, for it is not understood why the gearless elevator can have any advantage over the geared machine in this respect.

The discussion included a statement that a large number of contactors decreases the rate of acceleration. This all depends upon the inherent characteristics of the contactors. They can be designed to give quick, smooth operation without the necessity of making some contactors slower than others. With correct design of contactors the time element will not vary, but will remain constant indefinitely regardless of atmospheric conditions.

Mr. James says that with rheostatic control, the slow car speed will vary over a range of 3-1 or 4-1, depending upon the loads. This is probably true of rheostatic control of a single-speed motor, but is not true of one having a wide speed variation by shunt field control.

Undoubtedly Mr. James' remarks on the variable voltage system of control will be received by engineers with much interest. The two possible objections to this system are, first, the difficulty of "teasing" or "inching" for an accurate landing, and second, that the all-day power consumption may be higher than with other methods.

Mr. James points to the lost motion between worms and gears as an objection to the geared elevator. If the elevator machine is properly built, this lost motion does not exist and high speed geared elevators have been in regular service for many years without this lost motion developing. The probable life from a satisfactory service standpoint of the elevator worm and gear, is in the neighborhood of 15 to 20 years. The maintenance of the worm and gear is not a serious item. It has been proven by actual comparative tests that the d-c. geared elevator with a 3-1 motor shows power economy over the gearless elevator on any installation requiring not less than 50 stops per car mile.

David Lindquist: In the large expensive buildings being erected today, the whole venture may prove a success or a failure depending on whether you have adequate or inadequate elevator service. It is therefore of utmost importance to be able to predetermine the service conditions and the service requirements, because only by doing that properly can a satisfactory and adequate elevator equipment be installed.

In other words, the first, and most important thing is to provide adequate elevator service in a building. Second, you have got to provide reliable service. In other words, maintain such service under the most exacting and most severe operating conditions. Third, you must provide elevator service that is reasonably economical. Fourth, you have to have the quality of service. In other words, smoothness of operation, easy access to the car and egress of passengers, ease of handling, etc.

Mr. Reed's excellent paper calls attention to the necessity of taking the operating requirements or the service requirements of the building into account. Unfortunately, however, I feel that he hasn't sufficiently warned you against taking average figures, average data, and applying those to specific conditions. While the human beings are considered, and have been called "unit packages of freight," they are by no means unit packages or standardized as far as their size and shape is concerned, and when you come to the mental attitude and the psychology, then you will find even greater differences than the physical differences of size and shape.

The psychology of it is more important than anything else, because you will find that in certain buildings handling a certain crowd your average constants we will say for loading and unloading the car don't hold good at all. In other words, the average constants may give entirely too long a time. In other cases it is entirely too short. Take the hired help part of a modern office building today and you will find that you can handle them faster and more efficiently than most any crowd. On the other hand, in hotels and department stores, you have an entirely different situation. The majority of the patrons will not be of the rushing kind, and therefore you have got to allow entirely other time constants for handling passengers of that kind. Some of the figures mentioned in Mr. Reed's paper are averages, and no doubt good averages, but I warn you against applying those specific figures for special cases.

In connection with speeds and capacities, Mr. Reed mentioned 700 feet as very nearly the maximum speed. Mr. James pointed out that at the present time the tendency, particularly in New York and for high buildings, is toward much higher speeds. As a matter of fact, a thousand feet speed mentioned will probably not be the limit in the near future.

Now regarding passenger service in office buildings, Mr. Reed has given a table, giving the relation between rise in feet and suitable car speeds. Those figures are good averages, but may, under specific conditions, and in many cases, be considerably modified in order to suit the requirements.

Mr. Reed further mentions that for automatic push button service 300 ft. per min. is considered at the present time the speed limit. That is true with the method of push button control that has been used in the past, where one passenger has absolute control of the car to the exclusion of all the rest that may want elevator service.

Now push button controlled elevators have quite recently been very materially modified, particularly in reference to the method of control and the operating conditions. The method of controlling is substantially the same as with the car switch operated elevator, except that no car switch is required, and that the car stops in the direction in which it has been initiated at the desire of the passengers. In other words, there is no signal system except indicating that the car is going to stop at the landing, but no signals to the operator, and no operator in the car in many cases.

At the present time there is being installed in New York City an elevator installation utilizing full automatic push button control for 700 ft. per min., in a high class office building. The reason for that is not to slow down the service and get less service, but to increase the rapidity of service or the volume of service as well as the quality of service with a certain number of elevators over what could be obtained with car switch control at the same maximum speed of 700 ft. There will be a man on the car, merely a guard. His functions is principally pressing the buttons as floors are called out by the passengers in the car. In any sequence, depending upon how they call the numbers of the floors, in other words, they may call 17 first, 13 next, and 19 next, but in any sequence at all, the elevator will stop in proper sequence.

At the same time, assuming, for example, that the elevator is ascending, in case a passenger on any floor wishes to go in the up direction, the car will automatically stop for him in the up direction, without the operator or the guard in the car even knowing about the fact that the signal has been set or the stop has been set for the elevator.

Now that condition is somewhat modified by the control arrangement. An elevator may be in the up motion at the third or fourth floor. This elevator may be signaled to stop at the 19th floor for a passenger. In such a case that elevator is considered too far away from the 19th floor, so, therefore, the first elevator that reaches the 19th floor will stop there, although it hasn't been dispatched by the guard in the car to stop there.

On the other hand, if an elevator has been dispatched by the guard to stop at a certain floor and that particular car is waiting say four or five floors from that particular floor, then this mentioned elevator would stop at that floor, not only to let out passengers, but also to take on passengers, and all the other elevators that may be active will not get the signal to stop there. By that method the number of stops required for a certain service is materially reduced. You no doubt have noticed that frequently a car comes up, stops at the floor to let out passengers, and another car stops on signal at that floor to take on passengers for the same direction. That situation, of course, would be entirely eliminated.

For apartment houses the control is somewhat modified. The elevator runs on a round trip schedule. In other words, of course the complete run up and down takes on passengers and lets off passengers, as the case may be, and no operator or guard is required.

In department stores, for example, particularly where they are stopping at every floor, the guard's only function is to press the closing button for his door and gate and the closing of the door and gate will initiate motion of the car and it goes to the next floor, gets up to the top floor and reverses.

Mr. Reed mentioned that for department stores particularly, 250 feet speed is the accepted and correct limit. I don't quite agree with him. I believe that elevators can be operated satisfactorily and from an economical point advantageously at considerably higher speed. As a matter of fact, even 400 feet speed is probably not the economic limit.

Mr. Reed points out that the average number of stops in office buildings will be from 125 to 175. While that is true, it deserves further consideration. No attention has been paid, to the size of the car. That is a very important consideration, because if you have a large car, carrying a large number of passengers, the number of floor stops naturally will be increased, and if the car is very large, you stop at every floor, or practically so.

I would like to make some statement about the 75 lb. per sq. ft. loading as the accepted standard. While that is an accepted standard for the purpose of rating of elevators' capacities, a baseball crowd, at, for example, 181st Street subway station, pays no attention to the standardized loading of 75 lb. per sq. ft. The average is often over 100 lb. per sq. ft. and, as a matter of fact, we have records of as high as 115 lb. per sq. ft.

This, again, brings out the point that in order to put in adequate elevator equipment, you must know the service conditions.

Suggestion is made to decrease the speed of an elevator for the purpose of economy. Now that economy, in the example, is a false economy. It only deals with economy of power consumption, and not with economy from a broad point of view. Mr. Reed figures out that the interval of time, by using the higher speeds, is only decreased from 17.58 to 16.65 seconds, in other words, less than one second.

Looking into it a little more carefully, you will find that second is quite an important length of time. That difference in interval of time means in approximately twenty elevators you can save one. Now Mr. Reed has figured out that the power saved per year for ten elevators amounts to $288.00, for twenty elevators therefore it would amount to twice that, call it $600 per year. How much do you think that you save per year if you reduce the number of elevators from 20 to 19? Why, you save several times that amount in a building, because the space alone is worth considerably more than the power saved.

The statement is made about the half wrap traction machine that the principal objection is that the traction between the ropes and the driving sheave varies with wear of the driving sheave. That is true with the ordinary V groove sheave, but with a modified construction of sheaved grooving is not true at all. The traction remains with that construction just the same as it does on the U groove.

Now with the wear of the V groove naturally your pressure angle changes, and your traction is decreased. Now, on the other hand, if you want to make a single wrap machine, or half wrap, as Mr. Reed prefers to call it, out of this machine, all you have to do is to undercut your groove and as wear takes place your pressure angle doesn't change, and your traction remains practically constant. Mention is made that it is still an open question whether the full wrap or half wrap machine is the better. It is true, under certain conditions, the double wrap is better than the single wrap or the full wrap is better than the half wrap.

The statement is made that cable life is generally a little longer on the half wrap machine.

There again is one of those general statements that while true, are quite misleading. If you consider the total number of machines in service then it is true but on the other hand the great majority of machines with half wrap consist of geared machines, in which the sheave diameter is considerably larger, for various reasons, than employed with the double wrap, which has principally been used on the gearless traction machines.

One thing, however, is true about the half-wrap, and that is that you have got to be careful in selecting your sheave diameter and the number of ropes and the load per rope, and also the quality of the rope, because the surface pressure between the rope and the sheave is very much higher, and for the same traction effort is more than twice as high as it is with the U groove.

Certain trouble has been experienced due to the fact that this particular situation was overlooked, and in quite a few cases excessive wear of the driving sheaves has been found.

Another statement regarding the slower speed motor for the gearless traction machine. "That inherently means a very large machine." That is true, "and therefore, to keep the size down only a small range of speed is obtained by a change in shunt field." That statement is also true, but I think it is somewhat incomplete. I believe that it might be well to add there that due to the large time constant of a field of a large motor, for the sake of rapidity of acceleration, it it unsuitable to use a large field variation, even if cost was not considered.

In reference to duplex or tandem gear machines, I believe that his statement is somewhat misleading. I refer to this statement: "The field of the tandem-gear elevator is heavy duty continuqus service since it minimizes gear pressure by using three points of gear contact." Well, that is true, it has three points of gear contacts but only two of those are in contact with the worm. I made the general statement here that as far as I have been able to find, from my experience with geared machines, there is no advantage at the present time with a tandem-geared machine. As a matter of fact, a single-gear machine with properly designed thrust bearings, is superior to the tandem-geared machine. There may be cases where you, on account of space conditions, require a machine that is built on the style of a Los Angeles bungalow. There, of course, a tandem-gear machine has certain advantages. The tandem-gear really had its days when proper ball bearing thrusts couldn't be obtained.

I don't think that anyone would scriously consider it a cinch automatically to level a 600 ft. elevator by shunt field control or by frequency changing in an a-c. elevator and level that elevator automatically within an eighth of an inch, or say even a quarter of an inch of the landing sill. Still, by reading the author's statement I got that impression.

In regard to counter-weights, attention hasn't been paid to the fact that frequently it is necessary to modify the counterweight on account of lack of traction. Then there is a statement about the benefit of the flywheel effect for smooth operation. Now there again I don't think that anyone would seriously consider adding flywheel effect to an elevator motor for the purpose of obtaining smooth operation. Now I want to call your attention to the fact that the gearless machine, with the best operation, has the least possible flywheel effect. While it is true that flywheel effect may aid a poorly operating controller, I don't think that anyone would put in flywheel effect for that purpose.

I am just going to conclude with reference to rating of elevator motors. The statement that the 15 or 30 minute rating with full load is sufficient to determine whether that elevator motor would not overheat in service. Well, such a test has absolutely no significance, particularly when it comes to two speed a-c. motors.

H. P. Reed: We will grant, as has been stated in the paper, that the service calculation given, comes far short of covering all cases as it was not the intention of this paper to present details which could only be of interest to those directly connected with the elevator business. A complete treatment of this subject would in itself require a full text book.

The high-speed push-button elevator described by Mr. Lindquist, is very interesting and theoretically ideal, but as those experienced in the art will grant, the more complicated the device is made the more trouble is to be expected. In other words the advantages Mr. Lindquist claims is to increase the elevator service so as to reduce the number of elevators and save building space. However, in the scheme described it is feared that complications have been added which will increase maintenance to such an extent that it will require additional elevators to take care of shut-downs.

In the discussion Mr. Lindquist stated that the paper held 250 ft. per min. as the maximum speed for department store elevators. The average speed, which applies to about 12-ft. floor heights, was given as 250 ft. per min. in the paper, but it will be noted that the paper mentions a speed of 350 ft. per min. as a possible good maximum. This speed would be all right in a building having 15-ft. floor heights.

Mr. Lindquist said he felt the paper could not possibly mean what it evidently conveys, that floor leveling can be accomplished with a shunt field control motor, but as there are many in operation giving accurate results with this arrangement, there is no objection to interpreting the paper in this manner.

Mr. Lindquist touched briefly on heat specifications for elevator motors. This is a very good point and it is hoped that someone in the near future will come forward with a paper giving suggestions of specifications for actual installation heat tests for elevator motors.

J. J. Matson: There are two main points which I wish to discuss in Mr. Reed's paper. The first is the advantages and disadvantages of a high rotor moment of inertia; second, the application of alternating current motors to passenger elevators.

A high rotor moment of inertia increases the power consumption during starting. It also tends to increase the size of brake required. It has often been pointed out that service and smoothness of operation are two of the main features of an elevator installation. This is particuarly true when dealing with passenger installations. Provided a large moment of inertia is used, the smoothness of retardation and acceleration is improved. This is evident on account of the larger amount of stored energy in moving parts. The larger this energy compared to the power being required for moving the elevator the smoother is the starting and stopping.

Mr. Reed has stated that he believes the limit of a-c. motors on passenger elevators to be at approximately 350 ft. per min. I would take exception to this statement, inasmuch as there are several very satisfactory installations at the present time using a car speed of 425 ft. per min. Other installations have been recommended when using a-c. motors to run at 500 ft. per min. This I do not believe is too high a cage speed when using a-c. 2-speed motors.

The higher-speed equipments when using d-c. power supply uses a gearless drive. This consists of a low-speed motor, direct connected, to the driving sheave. A low-speed d-c. motor is a good electrical proposition. When you go, however, to alternating current, there are many inherent difficulties in reducing the synchronous speed so as to use a direct-connected motor. This can be readily understood when it is pointed out that in order to obtain a synchronous speed of 72 rev. per min. it would be necessary to furnish a 100-pole induction motor. Then when you consider that, in order to get slowdown for accurate stops, it would be necessary to cut this speed at least in a third, it is evident that a 300-pole low-speed motor would be desired. For the size of motor involved, this is at the present time practically an impossibility.

We, therefore, can consider that the a-c. installations must be of the geared type, and not only must the motor characteristics be considered, but also the gear characteristics must be considered. At the present time, I believe I am correct in saying that there are few elevator gears in operation at speeds exceeding 500 ft. per min. Undoubtedly, the elevator manufacturers can design and satisfactorily build higher speed gears and still obtain a very satisfactory device. It, therefore, appears that there are two limiting features: first, the gears, which is entirely the elevator manufacturer's problem; second, the motor, which is an electrical problem.

Relative to the electrical design of the motor, it would be possible to install a variable frequency and use this frequency instead of a difference in number of poles, in order to obtain slow downs. This same set could also be used in acceleration with the inherent degrees of power consumption. I believe that the use of a multi-frequency should be considered and investigated, as it certainly appears to be one of the several ways that will enable us to increase elevator speeds when using a-c. equipments.

H. P. Reed: Mr. Matson mentions that the paper gives the limiting speed of a-c. elevators as 350 ft. per min. At the time the paper was under preparation, this was essentially so, but since that time, at least one installation has been made of four elevators traveling regularly at 540 ft. per min. This speed was obtained by the use of motors having a 4-1 speed range.

Mr. Matson's further comments on a-c. motor design limitations will be welcomed by everyone interested in electric elevators.

A statement was made in Mr. Matson's discussion which pointed to the gearless machine as the only type used for the higher car speeds. Exception should be taken to this statement, as there are many geared elevators used on high car speeds.

E. B. Thurston: Reference is made to the downward tendency of elevators speeds. I don't believe it was the intention of the committee or the intention of Mr. Reed to give the impression that seems to be given. Therefore it is advisable to add to that a suggestion that it only applies to a high number of floor stops, because we all know there are installations of 600 ft. per min. where the elevator is stopping at practically every floor, and the higher speed is a very uneconomical installation.

In reference to that statement by Mr. James regarding the rate of acceleration, from our experience on the elevator side we fail to agree with him that the acceleration should be anything but constant. You cannot, it seems to us, change the rate of acceleration without its being objectionable to the passengers riding. There are many installations where this is quite evident. There are probably very few of you in the crowd who have not ridden on elevators which always start out too fast and objectionable.

A standard is mentioned in the paper of 5 ft. per sec. per sec. as quite satisfactory. If you exceed that very much it is objectionable to many people.

Mr. James also made mention of gears getting back lash in operation and stated that he didn't know of any installations where how certain principles had been applied to elevator gears. I would like to state that such principles as he mentioned have already been applied to elevator gears, and are working out very practically. He also questioned the possible rate of acceleration of geared machines. I would like to give him a test made on a geared machine operating at about 630 ft. per min. in regular service. Its rate of acceleration, with 1830 pounds unbalanced load on the car, was just 2¾ sec. It is possible with a geared machine to get and obtain any rate of acceleration, irrespective of the load and it stays put. It is interesting to note, because generally I have been an advocate of some shunt field control, the results that have been accomplished. With the gearless type of elevator it is not yet possible to build a motor with any appreciable amount of shunt field control. While the gearless machine is a simple mechanical machine, it seems to have sacrificed desirable electrical characteristics, all day operating efficiency, positive speed control, cost of maintenance and constant rate of acceleration, irrespective of direction or load. The results of the last two years of development to get a method of controlling the gearless machine have brought out many new and interesting features. It is interesting to note the use of the multi-voltage, the variable voltage control system, etc., but even with all these added it is still a big question as to whether it is equal to the economic running and cost of maintenance of the straight shunt field control.

H. P. Reed: Mr. Thurston no doubt refers to the statements appearing on page 328, column 1 in the third from the last paragraph. Mr. Thurston's comments are appreciated, as it is agreed that the statement could be much improved upon by adding the facts brought out in the discussion regarding the power economy with higher car speeds under certain service conditions.

It is felt that the statement in the paper is true for elevator service requiring an average of a stop for each elevator at every other floor.

W. S. Atkinson: Many of the larger cities and some states have elevator codes which prescribe with considerable definiteness the provisions that must be made for safety, and these frequently involve major features of design in the installation. For example, while 75 lb. per sq. ft. of floor area is generally accepted standard for determining rated capacity of passenger elevators, as stated in this paper, some codes prescribe 60 lb. for elevators in hospitals. There are also limitations in regard to the application of hand rope and hand wheel control, types of governors and "safeties," etc.

Hence, elevator manufacturers are not always entirely free in selecting equipment but must consult such local authority when it exists.

In the example worked out on pages 327 and 328 to determine the number of elevators required to serve a hypothetical New York Office Building, it is noted that the elapsed time from the departure of the car at main lower landings to its next departure therefrom, is designated as "time of round trip." In such calculations the writer prefers to apply this term to the actual time the car is away from the main terminal landing,—the elapsed time from departure of car to its return, which is actually a round trip. The distinction is of practical importance as affording a measure in comparison, excluding as it does the arbitrary allowance for lay-over or waiting time at main landing. The writer used the term in the sense here used in a paper some two years ago outlining this method of developing car schedules, but has abandoned it for the reason stated.

Also the wisdom of serving the sixteen story office building entirely by local elevators, as is here shown as an example, instead of dividing the 10 elevators into the express and local, will be questioned.

The majority of elevator installations going in today outside of the field of the high-speed gearless machine, are alternating current, and the importance of developments in motors and controllers for this application is to be emphasized. The advent of the two-speed squirrel cage motor and a realization that blocks of resistance in the primary could be used as a means of control have marked two important steps in recent successful extensions of the field of a-c. installation, the three-to-one speed ratio being the favorite. A very recent development is the six-to-one speed ratio squirrel cage motor where the low speed winding is made use of in approaching a landing.

H. P. Reed: From Mr. Atkinson's discussion, it is assumed that perhaps the paper includes some statements that are too definite. It was thought that some fairly definite statements should be made in order to bring out discussion. From the number of written discussions received, it appears that the paper has served its purpose in this respect.

Mr. Atkinson takes exception to the method of calculating the number of elevators required for an office building as given on page 327, column 2, in that all variable time factors are not introduced individually. It is felt that these factors carried through as one variable will give just as good results.

It is admitted that the question of whether all local or local with some express service elevators shall be used to serve a 16-story office building is open for discussion.

The same factors as given can be used directly by dividing the elevators up into express and local. In a building of this height however, it is felt that either method may be used with good success. With express and local service for the calculation given in the paper, the frequency of service cannot be less than 24 to 30 seconds, but it is possible to empty the building in a somewhat shorter period than with all cars running local. This condition means that the best elevator service can be obtained by express and local for the outgoing rush hour to empty the building quickly and at all other times all the elevators may be run local and still maintain a floor frequency service of 16 to 20 seconds.

Mr. Atkinson's remarks on the application of a-c. motors to high-speed elevators are most timely. The demand for such equipment is increasing by leaps and bounds, and it is only a question of time when more and more a-c. elevator installations will be made in the down-town districts of our large cities.

Theo. Schou: Gearless traction motors are being built with a speed of 50 rev. per min. with a full field. By weakening the shunt field, this type of motor may be operated at a speed as high as 85 rev. per min. with good commutation. It is believed that by a further study into this type of motor, a special design could be created whereby shunt field speed could be brought down to probably 35 rev. per min., giving a shunt field control from 35 to 100 rev. per min. Though this type of motor has a high running efficiency, the actual operating efficiency is probably lower than the geared machine, due to a rather less amount of shunt field control, necessitating considerable control by armature resistance. If this type of motor, therefore, could be designed with a lower shunt field speed, it would have a higher operating efficiency.

The name plate ratings of elevator motors should indicate starting torque and pull out torque, as well as horse power rating. This would give the elevator builders more definite information in regard to the motor from which to design their installations.

Direct-current motors in most cases have sufficient starting torque when provided with shunt field only; a 10 to 25 per cent compound winding for starting is only necessary for low speed heavy duty service. This compound winding is short-circuited after starting, and it is very difficult to completely short this winding under operating conditions, and therefore, difficult to obtain good speed regulation under varying load conditions.

Direct-current shunt-wound adjustable-speed elevator motors can be built with a speed range of one-to-four and still obtain, by special design, stable speed condition when running at high speed with a weakened field.

Both the single a-c. squirrel cage motors with stator windings for two or three speeds, with speed ratio one to three, or even one to six, and also slip ring squirrel cage elevator sets with a speed range of one to three are being built, and it is believed both these types of a-c. elevator motors have their place and will continue to hold their respective places in the future.

The slip ring squirrel cage motor is built as two motors, and assembled as a 2-bearing set, the low-speed squirrel cage motor being used for dynamic braking when run over speed.

It is true as stated in the paper that the future points to more developments and the supremacy of a-c. elevator motors in comparison with d-c. motors. In the past, there has been a great deal of objection raised to the noise of a-c. apparatus, including the motor, controller and magnetic brake. This trouble has been eradicated by furnishing motor driven control in place of the noisy magnetic control, and this has inspired motor builders to do all possible to remove the noise from their motors so that the a-c. equipment of modern type can now be procured for very quiet operation, and is controlled much better today than in the past.

H. P. Reed: Mr. Schou suggests a wider range of speed control by shunt field regulation for d-c. gearless traction elevator motors. This is a good suggestion, as a design of this nature will give the advantage of greater power economy, as well as more positive low speeds under different loading conditions. However, it is believed that Mr. Schou's suggestion of a maximum speed of 100 rev. per min. or even 85 rev. per min. is not practicable for a gearless machine with one-to-one roping as this would mean car speeds greater than allowed by law at the present time as it is considered that the approximate minimum diameter of driving sheave is 30 inches.

Arthur Liebenberg: The most significant statements in the paper seem to the writer to be

(1) That elevators of the worm gear type are now produced, giving perfect service at any speed up to 600 ft. per min.

(2) That the safety and economy of these types now seems to be superior to the gearless.

(3) That excessively high car speed is expensive and does not necessarily accelerate the traffic.

The writer would like to give a few added details of how and why this is true.

The tardiness of the worm geared elevators in claiming a place in the highest class of service has been due to the failure to perfect its details rather than any inherent fault of the type. The reverse is true of the type, for it was evident to the first inventor that the shunt motor had all the safety and other features needed but that some gearing was necessary to combine a commercially possible motor of 800 revolutions with a practically possible car speed requiring a 60 revolution drum. Nothing seemed more obvious than a worm gear and therefore it was the first used, and has been used for the lower speeds ever since. Only recently, however, designs and machinery have been perfected for producing commercially a satisfactory worm and gear. Today they can be produced, hobbed if you please, so they will run perfectly without any grinding in. The surfaces in contact are sufficient to give proper oil flotation so wear will not show in years of service.

The second factor that made the worm geared elevator for high speeds not only possible but most logical was the development of the interpole shunt motor.

The interpoles fix the point of commutation so that definite speeds can be obtained with variable loads by means of shunt field regulation.

The speed range for elevators having variable, positive and negative loads may be as much as 3½ to one.

All these speeds can be fixed within 3 per cent regardless of the load. Sparking or flashing on the commutator is avoided and heating need not be considered.

The motors are wound plain shunt except for the series turns on the interpoles. Some current is maintained in the field to give fast acceleration. For elevator work such a motor is ideal where direct current is available. For alternating-current, two-speed motors have now been developed having similar characteristics to the d-c. shunt motor. These also require gearing to keep the motor within commercial limits.

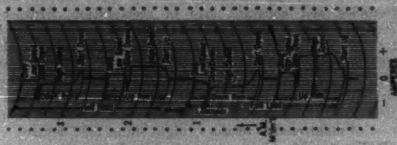
The interpole motor is desirable for elevator use because,

(1) In its economical speed range it is inherently safe from runaways for a wide range of loads.

(2) It has so much excess capacity at low speed that it can be given as fast acceleration as may be desired.

(3) The fixed low speed permits most accurate floor stops to be made. These stops are so definite that they can be made automatic if desired.

(4) The control is simple consisting of line and reverse switches and resistors in armature and field. The surplus power eliminates all questions of safety, leaving the problem of acceleration simple. With automatic and uniform timing of control steps the car accelerates in equal times regardless of the load.



220 volts. Each division 10 amperes. Read right to left.

FIG. 1—GRAPHIC AMMETER RECORD OF TEST

Elevator capacity 3000 lbs. at 400 ft. per min.

Motor	220 volts, 120 amperes
Full load starting current	60 amperes
Full load accelerating current	130 amperes
Full load running current	120 amperes
Full load running efficiency	70%

Power consumption between 2¼ and 3 kw-hr. per cm. mils for office building service.

It is economical because armature resistance, which is used only in accelerating up to the slow speed is all cut out when the car has traveled 12 inches. The field regulation used in accelerating above the low speed entails practically no loss. Dynamic braking regenerates the energy of starting and restores it to the line as useful current. See graphic ammeter curves in Fig. 1. The running efficiency is so near that of the gearless that these savings make its average efficiency much greater in any service where the loads are variable and the stops frequent.

Variations in speed in a standard shunt motor without interpoles amount to 15 per cent either from balanced load to positive or negative full load. Hence in a gearless equipment even with multiple voltage control the low speed for stopping will probably vary that much with differences of load. Hence while these expensive luxuries will improve the efficiency they leave the problem of making accurate stops to the second extravagance, the levelling device.

With the fixed low speed of the interpole worm gear elevator the power can be cut off at a point within about 8 in. of the floor and an accurate landing assured. The stop is attained with a combination of dynamic and two shoe brakes, one on the worm and the other on the drum itself. The drum brake prevents the slap from back lash that would occur when the direction of pull is reversed on the worm.

This brake has long been applied to the tandem worm gear but only recently to the single gear type.

Worm gearing is much more efficient than usually thought, not less than 95 per cent in the average passenger elevator units having 9 to 18 revolutions of the worm to one of the drum.

It is dependable and durable, showing little wear in 20 years of hard service. Ball or roller bearings are used to take the annular and thrust loads of the worm. The other bearings are provided with bushings of babbitt metal that are interchangeable.

Drum type traction, which the author did not describe, consists of a single chased drum on which the six ⅝ in. cables used are laid together, giving each one and one-half wraps of contact. When the elevator moves these cables travel together, along the face of the drum, a distance of a single groove for each revolution. This amounts to about 10 in. for 150-ft. run of the car. The standard idler traction described in the paper gets 2 half wraps so that slipping is usually imminent and the cables cannot be lubricated as they should. Further than this the idler triples the number of bends in the cables and the friction of the drum shaft and its idler. With the drum type of traction there is no slipping, and creepage due to differences of the average load is limited by a switch in the drum.

Readjustments of the cables is accomplished quite easily by running the car or weight on the buffers, relieving the traction.

Seven years of experience assured us that this system of traction is entirely safe and satisfactory.

Timing and the control of resistors with small motors through cams, one for the armature resistor and one for the shunt, has prove very satisfactory. It is very quiet in operation and lends itself to the proper adjustment of the acceleration to get the fastest comfortable rate.

Control is a prime requisite for good elevator service and the confidence born of smooth acceleration and accurate stops greatly accelerates the movements of the passengers entering and leaving the car.

The Warner Elevator Company has contributed largely to the development of the single worm gear elevator, which it has built exclusively since 1895. In 1915 it developed the ideal type described herein, which it has produced in large numbers ever since. It has given such good and economical service in high buildings that the makers of the gearless types have had to resort to multiple voltage control for groups of elevators and variable-voltage Ward-Leonard control for single units to meet this competition. There seems to be no warrant for the gearless equipment in buildings of less than 20 stories and not in them for local service.

W. H. Patterson: The variable voltage control system is an old principle and one thing that hasn't been spoken of very much here this morning was the noise and burning of contacts, on the control boards, which means cost of upkeep. That is one of the principal advantages in this system of control. We don't open any heavy armature currents, such as 150 or 200 amperes, but are merely handling field currents of three to five amperes.

Mr. James gave you a brief description of this system, so I will not repeat. But I would like to point out to you the current consumption that we recently got in tests which were made, on some elevators traveling 12 floors, with 2000 lb. load, at 500 ft. per min. With the balanced load and 75 stops per car mile, we got 1¾ kw.; with 150 stops we got 2¼ kw.; with 300 stops, 3 kw. With full load in the car and 75 stops per car mile we got 2¾ kw.; with 150 stops, 3½ kw., and with 300 stops, 4.7 kw. These tests show a remarkably low kilowatt consumption per car mile. They were made by our engineers and were recently checked by Mr. Bassett Jones of New York. He got practically the same results to the third decimal point. I therefore believe that this system of control warrants the attention of all elevator engineers and manufacturers. It offers the advantage, first, of smooth acceleration and deceleration; second, of low-current consumption; and third, low maintenance. The maintenance cost on your control board is going to be practically negligible because of the small current you are handling. Fourth, it solves the problem with a-c. current for high speed elevators. While great progress has been made in the last few years with two-speed motors, I think there is considerable developmental work yet to be done along that line to have it as satisfactory for high-speed passenger elevators as is the system of control such as this.

H. P. Reed: Mr. Patterson's discussion on the variable voltage elevator control is very interesting. It is felt however, that the power consumption tests do not tell the whole story on power economy. Test runs may easily be made with this system of control and show a considerable economy. However, it would be interesting to know just what the all day test will show, for instance, for an office building where there are not many stops per car mile, where the elevators are in service at least running not over 30 or 35 per cent of the time and where the standby losses of the generating equipment constitute quite an item in the power bill.

Bassett Jones: For the reason that not even an approach has been made toward a solution of the service problem in freight elevator engineering, I shall confine this discussion of Mr. Reed's paper to passenger elevator engineering. The passenger problem is relatively simple because, as has been said, "the passenger is a standard automotive package that stacks itself in one tier." However, this is only approximately true since the package in question has ideas of its own. But, being human, he does, in general, as all other passengers of his own class do, and so permits himself to be averaged as a member of a package group. Therefore there is some reasonable basis for treating the passenger as such a standard package.

As Mr. Reed says, service requirements form the premises from which the character, arrangement and size of the elevator equipment should be deduced. This point should be heavily accented. The determination of service requirements is the only logical basis for the solution of any elevator problem, freight or passenger. Given the service requirements, a determination of the most suitable size, duty, number, and arrangement of cars follows by mere arithmetic. But no amount of arithmetic will give the right answer unless the premises are sound. An error in determining the probable elevator service requirements in a building leads to a wrong determination of equipment no matter if the subsequent calculations be most precise.

Unfortunately the determination of service requirements must remain largely a matter of judgment based upon experience, and upon statistics gathered by painstaking observations. At best the answer is an intelligent guess, and so we have recourse to the best possible method of guessing—probabilities and frequency graphs.

Such studies in elevator services show that there are several important service factors, or rather coefficients, the probable value of each of which must be determined in each case before the probable service requirements as a whole can be properly established.

It is not merely a question as to how many people must be handled in a given time, but also what kind of people they are. Their working habits and group psychology must be determined. How promptly do they come to work, or leave, or go to lunch? How long can they be expected to wait in the corridors for a car without complaining?

All these and many others have to do with geographical location, vicinity to transit terminals, class and business methods of tenancity, etc. In these respects a bank building in Boston is not the same as a bank building in New York. Nor is an office building in down town New York the same as an office building in up town New York. Then, in office buildings alone, are the tenants, bankers and brokers with the attendant stream of messengers; are they professional; are they in insurance or in the textile trade? Are the tenants permitted to do small manufacturing such as clothing; will they in general occupy large areas with employees on the time clock, or will they occupy small areas and have few casual employees? These are a few of the questions that must be answered.

The renting management must also be considered. Today, many buildings are inadequately elevatored, but had they been rented differently, would have ample elevator facilities. A single large tenant occupying separated floors may entirely upset the assumed desirable schedule. In general, the larger the individual tenants the worse the conditions will be.

In addition the tendency of real estate development must be studied, also in a few years the building may prove to be hopelessly under elevatored, or, on the other hand, it may be stranded with a costly equipment on its owner's hands. The space of ten years has seen radical changes in the character of certain districts in our larger cities.

Having come to this point in our study, the next question relates to the probable total population that must be handled, either initially or ultimately. This will vary widely with the factors noted above. Depending upon these the population density may be anywhere from 40 sq. ft. rentable area per person to 200 sq. ft. rentable area per person.

The next step is to establish the probable rate of traffic flow, separately for the arrival period, for the departure period, lunch period, inter-floor traffic, and transient traffic. These, too, will depend on the locality, class, and working factors above enumerated. The arrival traffic may be anywhere between 20 per cent of the population in 15 minutes and 50 per cent of the population in the same time. The arrival traffic may be denser than the departure traffic or vice versa, and the departure traffic is more difficult to handle because of the absence of starters where it originates. Or, again, the combined inter-floor and transient traffic may be the determining factor in establishing service requirements. The location of toilets, restaurants, clubs, locker rooms—all must be considered as elements in the problem, and sometimes very important elements.

Thus, for example, measurements have shown that on the average, every woman in an office building visits the toilet, or woman's rest room, once an hour. Since 15 per cent of the population may be women, this means that 15 per cent of the population uses the elevators twice an hour, or 7.5 per cent in 15 minutes. Obviously the location of women's toilets has considerable bearing on our problem. Suppose the combined arrival and departure transient traffic is 8 per cent of the population in 15 minutes while the simultaneous business interflow traffic is 10 per cent of the population influx during 15 minutes. The net result including the female traffic is that over 20 per cent of the population use the elevators in 15 minutes, and this, due to the greater number of stops required, may be a heavier demand on the elevators than $33^{1}/_{3}$ per cent of the population arriving in 15 minutes during the morning arrival period. The 15 minute interval is frequently used as a convenient standard time measure. It is quite arbitary however.

Next we must know something of the probable distribution of the traffic flow during the worst period. What is its peak value and for how long does it last? Suppose that the average maximum arrival traffic during the 15 minutes is 25 per cent of population in this time. That is, during the worst 15 minutes 25 per cent of the population arrive at the building. During five minutes in this 15 minute period, the average rate may be 25 per cent greater than the 15 minute average, and allowance for this must be made unless crowding and delayed service is to result. Commonly, variations in traffic flow are observed by counting passengers entering the cars every five minutes. Graphs of such observations continued all day usually furnish a curious, and sometimes amusing commentary on the habits of the tenants. The character of the traffic frequency distribution will depend on the tenancy character factors previously mentioned.

I have devoted so much time to this sketch of service factors, because, after all, they constitute the basic data for our calculations. Without such a determination of traffic flow any method of determining the physical character of the elevator equipment results, as it begins, in a pure guess.

Questions as to corridor dimensions and arrangements as well as the size and types of door ways giving access to the corridors have not been mentioned above. As affecting the flow of traffic to and from the cars, such matters are of importance and should be studied.

Having covered these preliminary subjects, we are now in a position to discuss briefly the logical sequence of steps in the subsequent calculations.

We have established the probable traffic flow at the cars for arrival and departure periods, as well as the inter-floor and transient traffic and have selected one of these as determing the maximum service conditions. This selection may not be quite so obvious. In which case the computation will be made for the arrival traffic and then, as a matter of comparison, for the inter-floor and transient traffic.

Generally the computation will be started by assuming a desirable interval between cars. This, for the reason that the satisfactoriness of the service is determined by the interval or, what is the same thing, the maximum time a passenger has to wait for a car. On the average the car stands the full interval at the ground floor. This will vary with conditions of traffic. On the average a car travelling in each direction of motion passes each landing every interval. A car leaves the top landing every interval. Note that the interval taken is an average—it may be longer or shorter. If the interval, as an average, be taken too long in the beginning the maximum interval during the worst conditions may be out of all reason. Cases are on record where bad car design and restricted openings have increased the interval during a crowded period of inter-floor traffic to 4.5 minutes in a 16-story building. During the inter-floor period the traffic is equal in both directions, passengers both get on and off the cars at the same stop, and a crowded car, may and generally will, cause a considerable increase in the round trip time, lowering the interval. Frequently it is necessary to accept an inter-floor interval longer than the arrival interval.

Waiting for a car to arrive, or standing in a car that is not in motion, is the feature of the service that makes it seem either sluggish and slow, or snappy. Under these conditions 30 seconds seems 30 minutes to the impatient business man. It is entirely a question of passenger psychology, but it indirectly affects the rental value of a building.

In the highest grade office buildings in the New York financial district arrival intervals as short as 20 seconds have been used, but due to increasing population this is rarely maintained. A 24-second interval is considered good service; a 30-second interval is only fair service; a 40-second interval is slow service. The desirable intervals vary in different cities. In Boston, for instance, a 30-second interval is quite satisfactory.

Assuming a given interval as a starting place, from it must be deducted the time required to open and close car gates and landing doors at the ground floor to find the time available for handling passengers. For power operated gates and doors this deduction may be taken as 3.0 seconds. For hand operated gates and doors without car-landing door interlocks the deduction may be taken as 5.0 seconds, and with such interlocks 6.0 seconds or 7.0 seconds. The remaining time is available for unloading and loading passengers.

At the ground floor, where a starter is in charge, passengers can unload and load in 1.0 second each. At other floors the time per passenger will average 1.25 seconds with wide car openings, uncrowded cars and a reasonably effective means for announcing the arrival of the car at the landings. With crowded cars or restricted openings the time will increase. It is also increased in deep narrow cars. In crowded deep narrow cars the time may rise to an average of 2.0 seconds per passenger, and seriously affect the service.

Let us now assume a case. Assume arrival traffic amounting to 1000 persons in 15 minutes, and a 5-minute maximum of 416 persons. Assume a 30-second interval as desirable; hand operated gates and doors. Then the maximum number of passengers that can be loaded in the remaining 25 seconds is about 25. To prevent crowding a 30 passenger car should be used. But this is a very large car, and in office building service will run lightly loaded most of the day with marked unbalance and therefore at high average power consumption. Our traffic studies for this building show that the average load for the day will be 4 passengers, which, with the operator added, is a load of 750 pounds, and should be as nearly equal to the difference in weight between car and counterweight as it is reasonably possible to make it.

Let us then assume a 20-passenger car and either instruct the starter that only in emergency is he to admit more than 16 passengers, say during the 5-minute peak, or, cut down the interval to 25 seconds, which, as a matter of fact, is the best alternate, for then only 20 passengers can enter in the time available.

It is assumed that during the arrival period no passengers will be unloading since none will be coming down from the upper floors.

Let us then correct the interval to 25 seconds. Then in 5 minutes 12 cars leave the first or ground floor each carrying 20 passengers—a total of 240 passengers. But in this time during the peak 416 passengers arrive. Obviously the remaining 176 passengers must be carried in another bank of cars.

This second bank could have smaller cars than the first bank, but, due to possible shifting of population density in the building, it will be wiser to make all cars of the same size. The area of the car platforms should be 42 sq. ft. arranged 7 ft. wide by 6 ft. deep. The maximum load rating will be 3150 lb.

These cars, two wide in a bay, will require a double hoistway, about 16 ft., 4 in. wide by 7 ft. 10 in. deep clear inside dimensions. Unless service conditions demand that the steel work be designed to permit this, generally hoistways of such dimensions can not be obtained. This is one of the unfortunate factors in elevator engineering. Architects rarely consider the real importance of installing cars of the right size, compelling the use of a larger number of smaller sized cars at a greater first cost and operating expense. In the above case, it may be necessary to use cars 6 ft. wide, then a depth greater than 5 ft. 6 in. is wasted. The platform area is 33 sq. ft., the rated load 2500 lb. The maximum passenger capacity is 16 persons. The interval becomes 21 seconds if delays and waiting at the ground floor are to be avoided. There are 14.3 departures in 5 minutes, giving 228.8 passengers maximum per bank. The service is almost the same as with the larger cars at a longer interval as it should be, but more cars, or more expensive elevators of higher speeds and acceleration will be required to maintain the shorter interval. Thus the building structure itself also effects the situation. Let us, however, suppose that the larger cars at a 25-second interval can be used. We have now established the size of the cars, their maximum duty load and the number of banks.

To determine the number of cars in each bank we must calculate the average round-trip time in each bank. This, divided by the interval gives the number of cars, required in each bank. The calculations are given in extenso to show how and where the different variables enter in and affect the result.

For purposes of calculation the *round-trip time* may be conveniently divided into *running time,* or the total time the car is in motion, the *standing time,* or the time the car is at rest during its round trip, and *lost time,* or the time consumed in false stops, limit stops, synchronizing, etc.

The running time is best determined from time-speed data for the various types of hoisting engines. The best type to use is the one that makes the running time a suitable proportion of the round-trip time. This establishes the desirable velocity—acceleration characteristic of the equipment.

The *standing time* is made up of time consumed in operating gates and doors and loading and unloading passengers, at all stops above the first floor. To this is to be added the interval, or the time the car is standing at the ground floor.

Let us start out by taking the first bank. Let the building be 20 stories. The proportion of the population to be handled by the two banks is as 176/240 = 0.73, assuming equal population on all floors which may not be true. Then the first bank will feed 0.73 × 20 = 15.6, call it 16 floors. The hoist is 207.5 ft. on the average. The cars will stop at 0.8 of the landings "up," motion and none down motion. Therefore they stop at 0.8 × 16 = 10.8 landings, and the average "jump" or distance between start and stop is 207.5/10.8 = 19.2 ft.

On the way down the car makes one jump of 207.5 ft.

On the way up the car starts with full load and ends with no load, so its average load is half full load. On the way down it is lightly loaded. Therefore, it will travel faster on the way up than on the way down when maximum unfavorable unbalance exists. These differences may amount to a material item in computing round trip time.

The standing time is made up as follows:

Gates and doors, 10.8 stops at 5 sec.	= 54.0 sec.
Passengers, 20.0 × 1.25 sec.	= 25.0 sec.
Interval	25.0 sec.
Total	104.0

The time lost is—

One limit slow down at top	= 3.0 sec.
25 per cent false stops at 2.0 sec. = 0.25 × 10.8 × 2	5.4 sec.
Synchronizing	5.0
Total	13.4

The sum of the standing item and the lost time is 117.4 sec.

Let us try 8 cars in the bank, then if R be the running time, we have

$$8 = \frac{R \times 117.4}{25}$$

or

$$R = 82.6 \text{ sec.}$$

Assume a car on resistance control running at 600 ft. per min. 5.0 second acceleration time rated at balanced load. The time-speed curves for such a 1:1 roping direct drive hoisting equipment show that running down light it will accelerate just to maximum velocity and at once retard to a stop in 9.5 seconds, and will cover 60 ft. in doing it. The remaining travel at maximum velocity is 207.5 − 60 = 147.5 ft. which will be covered in 14.7 seconds.

This leaves 82.6 − 14.7 = 67.9 seconds running time up motion or 67.9/10.8 = 6.3 (nearly) seconds per jump of 19.2 feet with half load in the car. The time-speed data for this equipment show that the car will do this actually in just under 4 seconds. So there is a small amount of time to spare.

If power operation of gates and doors were used, 10.8 × 2 = 21.6 seconds would be saved. This, added to the spare running time of 2.3 × 10.8 = 24.8 seconds is practically two intervals, so two cars can be saved in this way, and the bank reduced to six cars. Without power operation of gates and doors, one car may be saved, making the bank seven cars. *Every time an interval is saved, a car is saved.* Obviously, the method outlined is subject to many variations. We might have started the calculation of the running time by assuming a velocity and speed and a type of hoisting engine, instead of assuming a number of cars. Then the running time would be calculated from the time-speed curves of the equipment assumed, next, the round trip time determined, and finally, the required number of cars obtained. The method is necessarily cut and try because there are inherently more variables than equations in the problem. It has the advantage over the method proposed by Mr. Reed that the variables are all put in one place where they are recognized as such, and can be given experimental values until the best solution is reached. Empirical formulas and methods are largely eliminated.

In one recent case I completed over 60 separate calculations before the best possible answer was found. But the resulting saving in first cost between the poorest and the best was in six figures, and the annual savings were in five figures. Of course, this was a very large installation in five banks of cars.

There are one or two other points in Mr. Reed's paper that I want to discuss very briefly.

The height of buildings are decidedly limited by the elevators—Mr. Reed says they are not so effected. If cost of space occupied by the elevators is considered, as well as building costs, it can be shown that in high grade office buildings on costly plots where taxes are high, it is not possible to economically elevator buildings above 26 stories in height in the usual manner unless the service to the upper floors be curtailed. When zoning laws affect the situation the 20th floor becomes the economic limit. The only recourse is to much higher velocity than the law now permits and to extreme acceleration. In order to make it economically possible to build a building 36 stories high in New York under the zoning law, it was found necessary to use cars reaching a velocity of 800 to 900 feet a minute in 3.0 seconds, requiring automatic voltage control and push button initiation of starts and stops otherwise entirely automatic. The owner desired a taller building so as to get more space, but it proved entirely uneconomical.

Unless the entire character of real estate development alters, such buildings are the future type, and, in them, elevators must attain velocities now unheard of. New types of control and operating devices will be necessary, and are, in fact just beginning to come into use. The additional cost of the elevator unit is little if the number required to furnish service can be reduced sufficiently. Nor does the increased power consumption at these velocities amount to a serious factor, for the saving of a few feet of rentable area can easily offset it. In fact, it is the overall cost that counts, and the power costs are but a minute fraction of the whole. Relatively speaking, reduced elevator speeds may save a penny here and there, but to offset this they reduce the whole rental value of the building, besides requiring more cars and consuming more rentable area. As a matter of fact, multi-voltage control may save as much as 30 per cent of the kilowatt hours required to give the same service with resistance control, yet this saving may be but a few per cent of the total consumption by the building and at a very low rate. The main value of such controls is not in saving kilowatt hours, but in making it possible to attain rapid acceleration, just as the principle value of the auto-leveler in passenger service is to make stops possible at high velocities. In general, both of these devices are essential for economic elevatoring of buildings 20 floors high or more. Where the stops are frequent, they may be worth while in buildings not so tall.

Mr. Reed suggests that a downward revision in car velocity is of advantage to the owner due to the lower power consumption of the low speed car. In my opinion this is an entirely fallacious argument. The reasons for this opinion may be best set forth by a specific case.

A particular office building in New York has 28 floors. Up to and including the sixteenth floor a proper service can be obtained with cars traveling at 600 ft. per min., attained in 5 seconds—the maximum conditions giving good operation and reasonable freedom from false stops with resistance control and car switch operation. With voltage control the same smoothness of operation and percentage of false stops can be obtained at 700 ft. per min. attained in 3.0 sec. The resulting average increase in service capacity is figured from the time-speed curves at 12 per cent. Therefore, in the total of 17 cars, as computed on the 600-ft. 5-sec. basis, 2 cars are saved, resulting in a net first cost saving of nearly $20,000. The kilowatt-hours are cut 25 per cent amounting to $2400 a year. Two operators are saved amounting to $3000 a year. Interest and amortization are reduced by $2400 a year. Maintenance is reduced by 5 per cent or $500 a year. Grade B rentable area amounting to 2500 sq. ft. is saved, which at $3.00 rental value is $7500 a year. The total yearly saving is $15,300. Of course, all figures are approximately to 10 per cent variation.

Above the sixteenth floor, a bank of 8 cars rated at 600 ft. 5.0 sec. is required. Changing to rating to 800 feet—3.0 sec. voltage control, auto-levelers to make stops possible under these conditions, and incidentally eliminating all false stops, with power operation of doors and gates, push-button car operation and grouped landing signals, reduces the bank to 6 cars. The saving in first cost is not material but there is a saving of 1900 sq. ft. Grade A rentable area at $5.00 a sq. ft. or a yearly saving of $9500. In addition the kilowatt-hours are cut 30 per cent and two operators eliminated. But the principal factor is the saving of rentable area amounting to 5 per cent of that total which determines the economic possibility of the building above the 20th floor. Numerous other similar cases might be cited.

In all of this I wish to draw your attention ot the necessity of determining running time from time-speed curves obtained by accurate methods such as by the oscillograph, and to the fact that empirical methods of estimating elapsed time between start and stop may introduce serious errors in computing the round-trip time. The obvious errors in the methods of estimating time by the scheme of calculation given by Mr. Reed must be eliminated. A large amount of data both of running time and standing time must be accumulated and reduced to frequency tables by which the coefficients may be intelligently classified. It will then be found that the average deviation from the mean can be reduced to a determinable probable value.

There is no present reason why velocities as high as 1000 ft. per min. should not be used. The only limit is the physiological effect on the passenger, not due to acceleration or to retardation, but due to rate of change in air pressure. Discomfort due to rapid acceleration can be eliminated by voltage speed control of the motors. The disagreeable effect so common with resistance speed control even at velocities as low as 650 ft. per min. attained in 5.0 seconds, is entirely due to the rate of change of acceleration being a variable. There is no discomfort when traveling at a constant velocity of any amount except that due to change in air pressure. The discomfort appears only when the velocity changes, and then, only if its rate of change be irregular, or perhaps if the acceleration or retardation be so excessive that the equivalent variation of the gravitational field increases the weight of the body to a point approaching the elastic limit of the muscles.

One other matter—the a-c. elevator. This is a matter of vital importance to the public utilities companies in our bigger cities. At the present time the velocities attainable are limited due to the inherent character of the a-c. motor, and not inherently in the control, as Mr. Reed states. It is a high speed motor and must drive the drum or sheave of the hoisting engines through a mechanical gear. High velocities via a gear of any ordinary kind are doubtful, although the writer is responsible for one such installation operating satisfactorily and economically with a car velocity of 400 ft. per min. I think it could be jacked up to 500 ft. per min. The motor used is a double affair—a two-speed squirrel cage and a slip ring on one shaft, the two stators in one housing. But at the higher velocities, d-c. direct drive hoisting engines on proper voltage control can be operated from an a-c./d-c. motor generator set at less over-all power consumption than required by the d-c. hoisting engine on resistance control—in many cases this saving will be sufficient to pay for the added cost of the voltage control, particularly where the change to a-c. service brings about a reduction in rates.

H. P. Reed: Mr. Jones mentions that no solution is given of the service problem on freight elevators. The service problem on freight elevators is so varied that it requires a special solution in each case, depending on the use of the building and the method of handling material.

Mr. Jones goes into some details on the service problem which is felt are not of particular interest to the electrical engineer. We must take exception to his maximum population density of 40 sq. ft. per person. This means but approximately 6 x 6 feet of space per person, which is felt is almost impossible inasmuch as rentable areas is understood to include closets, safes, partitions and all lost space outside of corridors.

Mr. Jones takes exception to the method of calculating the number of elevators required for an office building and favors the introduction of each variable factor, whereas it is felt that these factors carried through as one variable will give just as good results.

In the discussion, a criticism was made of a statement that height of buildings are not limited by the elevators. In making this statement it was not intended to include commercially economical construction of any particular building due to the size of the plat or the shape of the building. As far as the mechanical and electrical features of the elevator are concerned, they can be built for any height of building.

Mr. Jones' criticism of the suggested saving due to slower speeds was answered by Mr. E. B. Thurston's discussion.

The discussion mentioned that a 30 per cent power saving can be realized by applying multi-voltage control in place of rheostatic control. This may be so for the elevator machine as a unit, but it is felt that the stand-by losses of the generating equipment producing the various voltages will off-set to a large extent any possible power saving.

Mr. Jones mentions the advantage of the auto-leveler in passenger service in order to make reasonable stops at high velocities. While this may be true in some types of motors and control, it is not true of some other types. The use of shunt-wound d-c. motors with a wide range in speed control by shunt field regulation and a constant time element acceleration control provides an equipment which will give accurate slow speeds and practically constant rate of acceleration, regardless of load conditions. Therefore, with equipment of this nature, accurate stops can be quickly made without the aid of the auto leveler.

According to Mr. Jones the paper mentions that the limitation of speed of elevators driven by a-c. motors is due to inherent control limitations. We fail to see where this statement appears. No such limitation exists as successful installations of passenger elevators driven by a-c. motors are now operating 540 ft. per min.

It is granted at high velocities with an *ordinary* gear, but as stated previously in the paper, it is being proved daily that if correctly designed and constructed a geared elevator is giving as smooth and satisfactory operation as any gearless type, and with greater economy. Moreover, as the multi-speed a-c. motor can be successfully applied to the higher elevator car speeds, there is no need for the transforming to direct current with the resultant stand-by losses.

H. L. Wallau: In all of our larger cities we have the d-c. system of distribution in what is generally known as the downtown or business area. This development came about very naturally, due to the fact that the Edison System was the first developed and the cities that are now the largest cities, were the largest then, and had the initial electric systems installed. However, there are a great many of the medium sized and smaller cities in which the Edison system is not in use, and a-c. current only is available, or in certain cases special 500-volt d-c. elevator circuits are run.

Now these smaller cities are gradually getting into the class of the larger cities, larger buildings are being erected, so that they are becoming metropolitan in character and high-speed elevator service is required. It is therefore very gratifying to note that an installation is being made in Toledo today in which three hydraulic elevators are being replaced by a-c. elevators with a speed I understand of 550 ft. per min. I have been told, although I haven't personally inspected the elevators, that their operation is very satisfactory, quiet, the acceleration is smooth and the development begins to have very hopeful possibilities.

Mr. Hellmund: It occurred to me in this discussion that there was too much reference made to the speed of the elevator when a-c. and d-c. service is compared. It is not so much the speed of the elevator that limits the application of the a-c. motors as it is the number of stops that are made. The two-speed squirrel-cage motor, which is now applied to some extent to elevators, will give excellent service if the number of stops is not too frequent. As is well-known, all the starting energy and the braking energy, from the high speeds to low speed, is dissipated in the motor, and therefore the number of starts and stops is of utmost importance with regard to the motor heating.

In this connection I should like to refer to one point in the paper where certain calculations are given about the loading of the motor. With a squirrel-cage motor, it is not only a question of what the load is, but it is also very important to consider how often it has to start. If one goes too far with the frequency of starting, overheating will result even with zero load. For this reason, I believe that the two-speed a-c. elevator motor, while undoubtedly having a large field of application, cannot be applied to everything. When it comes to frequent starts, something else has to be used.

One possibility for such cases is the two-speed motor with wound secondary, which is, however, not a very elegant solution of the problem on account of the many slip rings and the complicated control.

Another possibility, previously mentioned, is the Ward-Leonard system of control changing from a-c. to d-c. power. This certainly has a number of attractive features and, for the higher class of elevator with frequent starts, it looks like an excellent proposition.

Reference has also been made to the possibility of obtaining adjustable speeds for a-c. motors by means of frequency changers. The Westinghouse Electric and Manufacturing Company has an installation in operation where frequency changers have been applied with good success. Of course, this requires an extra piece of rotating apparatus, and if such is used, it is perhaps just as well to convert to direct current and have the additional advantage of being able to use the direct traction arrangement, which is almost impossible with a-c. motors.

Another point which has been briefly mentioned in the discussion is the question of noise. One of the speakers stated that a-c. motors can now be built so that they are not so noisy. That is somewhat optimistic. In connection with the noise problem, we must realize that it is largely a question of natural periods and resonance of various parts, and no engineer is able to calculate the natural periods of the various parts entering into an elevator installation. Motors may be quiet in one place or one position, and when they are put into the penthouse, they may vibrate on account of the resonance effect of the floor. Therefore, we cannot claim that the noise problem is fully solved. But there are certain predominant causes for noise, which are now more fully understood than in the past, and therefore the matter is not altogether hopeless. I think we shall be able to equip the large majority of a-c. elevators pretty soon so that they can be called practically noiseless or, at least, not any noisier than the d-c. installations.

H. P. Reed: The author hopes that the paper with discussions will be of value to architects, engineers and to everyone connected with the manufacture and use of electric elevators. Perhaps more real active engineering problems are occupying the attention of the elevator engineers today than at anytime in the history of the elevator business. Many of these problems are but briefly mentioned in the paper, but are deserving of further study. It is hoped that further elevator papers will soon be available, particularly on the following subjects.

(1) High-speed elevator travel using a-c. motors.
(2) Variable voltage control (Ward-Leonard system.)
(3) Automatic leveling devices.
(4) Multi-voltage control.
(5) Door interlocking equipment.
(6) High-speed push button and dual control.
(7) Actual comparative test results of power consumption for the many types of machines, motors and control.

The Improvement of the St. Lawrence from the Viewpoint of Private Capital

BY HUGH L. COOPER

Consulting Engineer, New York, N. Y.

THE subject of the reconstruction of the St. Lawrence River, and the results to be obtained therefrom, lead us into magnitudes that are very difficult of practical visualization. In order that you may be properly oriented I would like to refer you to the map, Fig. 1. In the course of my remarks I will call your attention to a general plan which I have worked out for a part of this reconstruction, and will give you a general description of my ideas as to what should be done with the remainder of the river. It is my present belief that the best public interest demands that the St. Lawrence River should be harnessed by the construction of five dams; the first one being located at Cat Island above Massena, the second at the foot of the Long Sault, the third at the foot of Cedar Rapids, the fourth at Cascades Point, and the fifth at Cote St. Paul.

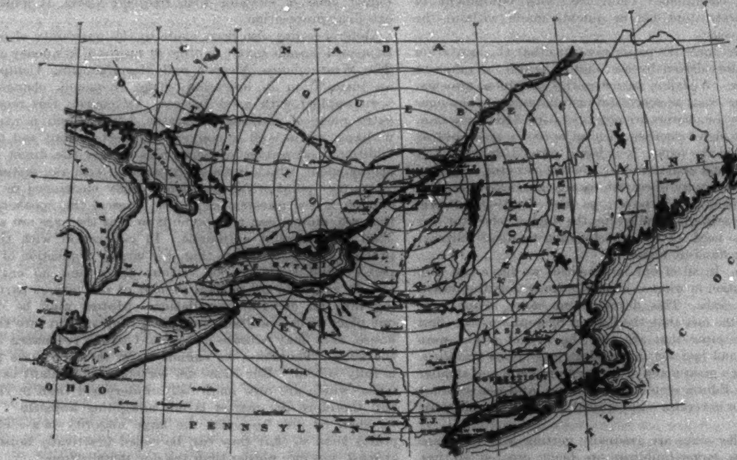


FIG. 1—POWER TERRITORY AVAILABLE FOR ST. LAWRENCE POWER IN CANADA AND THE UNITED STATES

Transmission line distances will average about 115 per cent of the distances shown by the circles that center at Dam No. 1. The territory within these circles and within circles that can be drawn using Dam No. 5 as a center can be served without invading any experimental field.

Before we go further, I wish to tell you very plainly that I am not flattering myself that I have solved the St. Lawrence problem. Later, very necessary investigations may show that dams Nos. 1 and 2 should be combined. I believe that the judgment of no one engineer will ever be accepted for work of this magnitude, and that before any engineer's plans are adopted, they will have to pass successfully through the acid scrutiny of a high grade commission of engineers from Canada and America, the personnel of which, when examined, will show that the Commission is qualified to the fullest degree by previous experience, to write the verdict.

DIVISIONS OF THE SUBJECT

I desire to divide our St. Lawrence subject into the following divisions:

First, private capital personnel and proposal.

Second, the attitude of water power people toward navigation.

Third, with reference to the magnitude of the work as a physical structure.

Fourth, six new great values to the public from a reconstructed St. Lawrence River.

Fifth, how St. Lawrence benefits should be achieved.

PRIVATE CAPITAL PERSONNEL AND PROPOSAL

It has occurred to me that I should clear up the minds of this audience as to the honesty of a small amount of propaganda that still remains with us about

Address delivered at the Spring Convention of the A. I. E. E., Chicago, Ill., April 21, 1922.

the so-called water power trust. I assume that in the public mind, a proper definition of a trust would be an organization which could, because of its holdings either of rights, or property, or both, rob or hurt the people without hindrance of law. As I read a few of our newspapers, this definition seems to fit the case. The studies which I have been carrying out on the St. Lawrence for about three years have cost the interests that supplied the money, something over $250,000 for engineering research, and $500,000 more is ready to complete our investigations, as soon as governmental permits are granted. This money has been furnished by interests who own the Frontier Corporation of the State of New York. It is opportune to state here very plainly that the Frontier Corporation has never been engaged in any propaganda in the past, and will refrain from such methods in the future. We have not asked for, nor will we be seeking the support of any particular section of the press. When the St. Lawrence question is fully understood it will be regarded as a national problem in which the points of the compass must be omitted. As we are asked for our views by the press, by government officials, and by the general public, we will gladly give them the facts, and stop there. Our well defined expectations of success are based entirely upon the good sense and intelligence of our people to decide what is in the best public interest.

The members of the Corporation at this time are, the Du Pont Company, the General Electric Company, and the Aluminum Company of America. They have been brought together because of the belief that no lesser syndicate of successful men of industry could cope with the problem from a private capital standpoint. The carrying out of a project of the magnitudes here under consideration, will call for the very best intellects that America can produce, and the American people have a right to demand that when the St. Lawrence work is finished, by whomsoever it is constructed, the work shall represent a magnificent monument to American ability. Such a monument can never be expected to result from government ownership, or from the leadership, however earnest and honest, of merchants, railway men, lawyers, doctors, newspaper men, or others; it can be expected to come about only by the combined efforts of organizations which are familiar with the work to be undertaken, and whose records with great enterprises are successful.

The Aluminum Company of America, as you may know, has spent several millions of dollars in the purchase of lands along the Long Sault stretch of the River between its Massena intake and Cornwall. When the purchases of these lands were made, it was hoped at some future time to develop water power on this property for use in metallurgical chemistry. Over two years ago the Aluminum Company came to the definite conclusion that this great water power in the St. Lawrence was of far more value to the public if used for general distribution to little and big consumers, than it was of value to the same public through the consumption of aluminum, and some time after reaching this decision, the Aluminum Company passed the control of all its holdings to the Frontier Corporation.

At the time the Frontier Corporation was formed, over a year ago, and for some years before that time, all of our syndicate members were fully aware of, and in complete accord with the provisions of Federal and State Laws that require, individually and collectively, the most thorough supervision at the hands of public service commissions, state water power commissions, and the Federal Water Power Commission, of all of the energy that could be created from the St. Lawrence or any of our other navigable streams. Under the operation of these laws which I have just mentioned, the rates to be charged to consumers, the character of the service, the territory to be served, and the issuance of securities, are all in the hands of public service commissions, the servants of the consumers themselves.

The members of the syndicate have entered upon this endeavor with the full knowledge of all of the restrictions that I have just mentioned, and with which you are all so familiar, and to call such an association of men a "trust" or a "power ring" is plain dishonesty. No good person seeking the truth can ever accuse the Frontier Corporation, and the men behind it, of having anything but the highest aims in this whole matter. It is further proper to say at this time that the quantity of money required for the first unit of installation will be so great that the interests behind the Frontier Corporation, strong as they are, can never be anything but leaders and holders of a small minority of the total securities that will necessarily be sold. The majority of the securities will have to be taken by the public at large. This investing public will never subscribe to these securities if their attractiveness is clouded by propaganda of abuse and misrepresentation in any considerable amount. Before the Frontier Corporation, or any other corporation, can finance units of development on the St. Lawrence, it must prove to governmental authority, and its prospective investors, that its financial and engineering plans, after full official inquiry, have been found not only the best that can be devised in the public interest, but superior to all other plans considered.

The members of our syndicate have an abiding confidence in the ultimate fairness of American and Canadian people, and believe they will eventually accord us the approval we must have. We realize that much patience will be required on both sides, and we believe when the cards are all on the table, where they should be, neither the people nor we will have much to complain of.

ATTITUDE OF WATER POWER TOWARD NAVIGATION

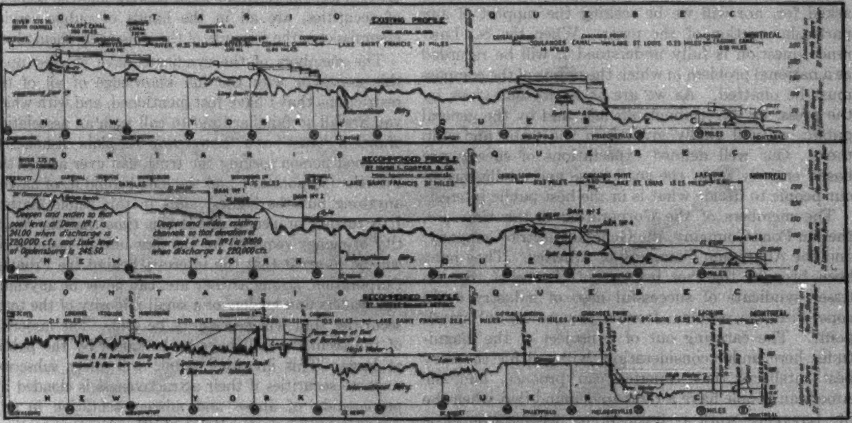
Over the St. Lawrence River there is now transported annually about 4,000,000 tons of freight, a few passenger steamers, and there is developed at present from the St. Lawrence less than 200,000 horse power. For some time in the past, our friends of the opposition, in different places, have been trying to create a false impression regarding the attitude of the water power people toward navigation. This attempt was wrong because it was based upon falsehood. The opposition should have given us credit for more intelligence than to suppose that any group of men would, for a moment, consieer the mutilation of, or encroachment, in the slightest degree, on the great transportation facilities the Great Lakes and the St. Lawrence can offer to more than 40,000,000 existing people, to say nothing of the vast increase in this population future time will record. That navigation is paramount to power, every one concedes, and I know of no one who has ever disputed this view, whose opinion is worth noticing. The laws under which we are hoping to operate, specifically make navigation paramount to power, and require that all of the water levels in the pools shall be regulated in the interest of navigation, by government.

We have always known, advocated, and maintained that by the right of the people, by existing law, by common sense, and by every other avenue of good reasoning, power is secondary and incidental to navigation, now and always will be.

Physical Magnitude of the Proposed Plans

The stretch of the St. Lawrence River under consideration is 120 miles long from Ogdensburg on Lake Ontario, to Montreal, and drops, in this stretch, about 220 feet—approximately 200 feet of which is available for power purposes.

You are, of course, aware of the fact that the International Joint Commission, created by the Act of Congress, January 11, 1909, has recently made a report to the Governments of the United States and Canada, on the subject of the reconstruction of the St. Lawrence River, based upon the recommendations of their respective government engineers. Open criticisms were called for by the International Joint Commission of the Government Engineers' report, and I have filed with the International Joint Commission comments on the Government Engineers' report. I have found myself unable to agree in any sense with the recommendations of the Government Engineers, and believe the adoption of their plans would constitute a most extraordinary mutilation of a great international engineering possibility. This sweeping opinion is fully shared by every hydraulic engineer of experience I have consulted, and I have consulted several of them. I do fully agree, however, with the recommendations of the International Joint Commission to the effect that because the problem before the Commission was of such great magnitude, the whole subject should be referred to a new enlarged commission of engineers whose previous experience in work of this character would be acknowledged everywhere as of the highest acceptability.



O N T A R I O
Q U E B E C
N E W Y O R K
EXISTING PROFILE
LAKE SAINT FRANCIS 31 MILES
LAKE ST LOUIS 15.25 MILES
MONTREAL
International Bdry
RECOMMENDED PROFILE BY HUGH L. COOPER & CO.
LAKE SAINT FRANCIS 31 MILES
DAM Nº 1
DAM Nº 2
DAM Nº 3
DAM Nº 4
DAM Nº 5
Deepen and widen so that pool level at Dam Nº 1 is 241.00 when discharge is 220,000 c.f.s. and Lake level at Ogdensburg is 245.50
Deepen and widen existing channels so that elevation of lower pool at Dam Nº 1 is 200.00 when discharge is 220,000 cfs.
RECOMMENDED PROFILE
LAKE SAINT FRANCIS 22.5
21.5 MILES
23.00 MILES
10.5 MILES
Power House at End of Barnhart Island
High Water
Low Water
Canal
Dam & Pit between Long Sault Island & New York Shore
Spillway between Long Sault & Barnhart Islands
Ogdensburg
St. Regis
St. Anicet
Valleyfield
MILES

Fig. 2—Three Profiles of the St. Lawrence River

1. Existing profile.
2. Profile recommended by Hugh L. Cooper subject to such changes as final surveys require.
3. Profile recommended to the International Joint Commission for adoption by the Wooten-Bowden engineering report.

I shall not take your time in an extended review of my differences with the Government Engineers' report, but will instead give you a very brief outline of what they have proposed, and what I have proposed, and will refer you to the comparative profiles shown in Fig. 2. The Government Engineers propose the installation of three dams in the St. Lawrence, nine locks, thirty-one miles of canals, and the installation of 4,545,000 horse power capacity, at a grand total cost of $506,000,000, without any interest during construction, or during the loading period for the power, and all of this for power houses that would, if operated to capacity, automatically shut down in times of ice attack. In my opinion, this $506,000,000 cost estimate is not only valueless because it excludes interest, which has to be paid as well as principal, but it is otherwise valueless because the estimate is on structures that sadly fail to produce the best efficiency either in navigation or power. My plans call for the installation of five dams in the St. Lawrence, six locks, six miles of canals, and 5,400,000 horse power capacity, at a total cost including all charges, from one billion, two hundred and fifty million, to one billion, four hundred million dollars, depending on results of final surveys.

I will now direct your attention to the Figs. 3 to 19 inclusive, which will illustrate better than words, the general power situation, as I see it.

Because of the greater ratio of pools to narrow canals, my navigation plans provide for 25 per cent greater speed, and much greater safety through the St. Lawrence than the Government Engineers' plans provide for. They have thirty-one miles of canals, and nine locks, where I have six miles of canals, and six locks. In all other navigation requirements, my plans are either equal or superior to the Government plans. In addition to producing far better navigation facilities than those proposed by the Government Engineers, my plans produce 855,000 more horse power capacity for general use, 550,000 horse power of which is in the international stretch of the river. The public in Canada and the United States will never consent to throwing away navigation facilities and power in the way the Government Engineers have recommended. Some day our St. Lawrence Tidewater Association friends will see and admit the inferiority of the Government engineering plans with respect to both navigation and power, and the superiority of our plans with reference to the same subjects.

Six New Great Values to the Public from a Reconstructed St. Lawrence River

The first value to the public from a new St. Lawrence, if Mr. Hoover, Mr. Barnes, and many other high authorities on this subject are correct, will be the creation of a permanent link in a navigation system capable of handling 200,000,000 tons of freight per navigation season. As soon as the Great Lakes district is completed to the same capacity as the St. Lawrence, there will thus be created the greatest inland navigation facility in the world, producing permanent distinct advantages to producers and consumers alike.

Second, the saving of coal and labor. As to the value of 5,400,000 horse power that can be commercially developed from the St. Lawrence River on a load factor varying from 70 per cent in the winter to 80 per cent in the summer, 1,200,000 of this horse power would belong to the United States by treaty right, and 4,200,000 to Canada by the same right. Inasmuch as Canada already has a superabundance of hydroelectric power in the vicinity of the St. Lawrence to supply her needs for decades to come, it is probable that at least a part of this power can be used in the United States until the Canadian markets require it.

The statistics of the United States Government show that 5,400,000 horse power will save more than 54,000,000 tons of coal per annum. It is difficult to visualize numerals of this magnitude. Using fifty-ton coal cars as a basis, 54,000,000 tons of coal would make a railway train 9000 miles long, a distance greater than the diameter of the earth, and over three times the distance between New York and San Francisco. At the ordinary rate of coal transportation, 54,000,000 tons of coal would make 1,080,000 carloads, 36,000 engine hauls of 150 miles each, and require the use of 5000 railway men, to say nothing of the labor of 70,000 men used to mine the coal, and 80,000 other employees who would automatically be released for other uses.

Third, the saving to railroad property of the United States and Canada. A careful study of reliable statistics shows that every new hydroelectric horse power installed automatically releases something over $100 worth of coal carrying railway property for other general uses. The substitution of 5,400,000 hydroelectric horse power for coal generated power will relieve for other more useful purposes, $540,000,000 of existing railway property in the United States and Canada, and thus relieve the investment field of the need of furnishing this great sum for new railway construction and equipment.

Every well-informed person knows that for many years in the past, the railways in the United States have been handicapped in carrying out needed extensions of all kinds because of lack of funds, and that when our business revives, as we all hope it will some day, the railroads will be behind in capacity to handle freight. Any proposal that will relieve the demand upon railroads (and we of course furnish most of the coal Canada uses) is, as a matter of fact, a blessing to our railroad systems as a physical machine, and therefore, a blessing to the people themselves who in the last analysis really own the railroads. Some people seem to think that the president and board of directors own the railroads. The stockholders own the railroads. When the late James J. Hill died, he owned only 3 per cent of the stock of the Great Northern Railroad, if the newspapers can be believed.

Fourth, the saving in power bills. The construction, and putting to work of 5,400,000 hydroelectric horse power will save power consumers in the United States and Canada at the rate of $35 per horse power per annum, or $189,000,000 per annum, figuring pre-war coal costs which, of course, we all know will never again be available. This great annual saving in power cost will be a tremendous aid to industry in both countries, that can not be secured in any other possible way.

Fifth, the impetus to new industries by the placing of St. Lawrence power in Eastern Ontario and Western Quebec, New England, and New York, and also along the 354-mile length of the Erie Canal, will create demands for labor and material of great benefit to the public on both sides of the international boundary line.

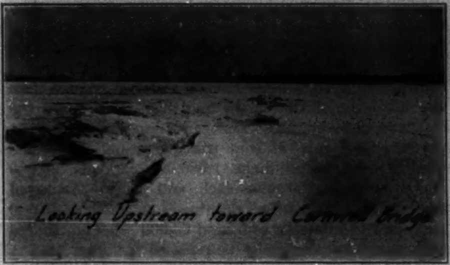


Fig. 3

Fig. 4

Fig. 5

Jam Head Cat I
8/5/20

Fig. 6

Figs. 3, 4, 5 and 6 show average ice conditions in the St. Lawrence that navigation and power structures must successfully control. At times more than 675,000 tons of ice per hour will have to be automatically controlled if navigation structures are to continue safe and if power plants are to operate to capacity. The history of eleven power plants at Niagara Falls and on the St. Lawrence, covering approximately fifteen years, shows that in attempting to handle but a small portion of the total ice moving, all but one of these eleven plants, that of the Toronto Power Company, have suffered annually severe ice interruptions to a degree that would seriously interfere with satisfactory long-distance transmission. If power from the St. Lawrence is to be made available for the territory under consideration, the ice problem must be absolutely solved by using the engineering principles that have stood the test at the Toronto Power Company's plant on the Canadian side at Niagara Falls.

Sixth, the reconstructed St. Lawrence plus the Niagara power potentialities present and future, will give to the territory extending from Detroit and Windsor on the west, to Quebec and Bangor, Maine, on the east, a continuous power zone in which more than 8,400,000 hydroelectric horse power will be available for industry at practically the same average price on both sides of the line. History does not record a single case in which one of the two bordering countries is continuously prosperous at the expense of the other. The best prosperity is founded always on a full consideration of the "live and let live" policy. The juxtaposition of cheap navigation and cheap power will produce industrial prosperity on both sides of the line which will never be forced to respect, for any great length of time, any international boundary. This prosperity will flow everywhere by the laws of good sense and good economics, as the people are educated up to where they can see the permanent value of genuine reciprocity.

The foregoing six great values are in reality economies with a vengeance, and we should use them before vengeance is upon us for their non-use at a time when economic conditions not only existing, but for decades to come, require our use of every possible economy, if our industries are to survive European and Asiatic competition.

All of these six new great values (and more could be enumerated if time permitted) can be supplied to our people on both sides of the international boundary line without hurting any public or private investment or good purpose, and what is more phenomenal still in the accomplishment of these great results, navigation will not be called upon to sacrifice a fraction of an inch of navigation depth to water power, and water power will not have to yield a fraction of a horse power to navigation. Surely any set of men who are seriously proposing this great work, and who, with all of the resources of leadership, men, and money at their command, will assume all the risks involved, and will bring about such a consummation in the public interest, deserve and will receive the full support of all of our good people.

How St. Lawrence Benefits Should be Achieved

The question is, how shall this need be supplied, and we are led at once into the age-old controversy of public versus private ownership. The advocates of both of these views are undoubtedly sincere. Twenty years ago before public service commissions had demonstrated their usefulness, too many corporations were guilty of the "public be damned" policy, and the public service commissions were, therefore, the normal result. Thanks to the good work accomplished by these public service commissions the controversy as between public and private ownership is, in my judgment, rapidly coming to a close. The war in a great way demonstrated to us the evils of government management in large affairs. Most of the intelligent people of the United States are now convinced that well regulated private corporations are the best for everybody, as opposed to the inevitable inefficiency that has always been found in government management of business. The history of the Hydro-Electric Commission of Ontario, as it is today being sadly written, is final and convincing proof of the inability of governments to successfully handle great public utilities.

In view of its influence on the whole St. Lawrence situation, I desire to call your attention very briefly to the unusual conditions which have developed in power production at Niagara Falls on the American side. You are aware that in the early nineties when Niagara power first began to take shape, progress in the art of turbine and generator design, together with the scarcity of a reachable market, compelled the use of only a fraction of the total head in the Niagara River. Plants using from 40 to 60 per cent of the total available head were accordingly installed. These fractional heads resulted in the proportionate inefficient use of the water, but it was a case then of inefficiency or nothing. The public everywhere properly acclaimed the courage of these early pioneers in going forth with these new enterprises at a time when so little was known as to what the ultimate destination would be. Hydroelectric engineering all over the world is greatly indebted to the early installations on both sides of the line at Niagara Falls for the experience thus made available in aid of the succeeding advances in hydroelectric engineering. Now, because of great increases in the demand for power, governmental authorities on both sides are requiring that the old diversions at fractional heads should be abandoned, and the water used at maximum efficiency. This requirement has called for the absorption by the new efficient plants of the great sums originally invested in the partial head plants. This union of costs will result in making the present and future cost of generation at the busbars on the American side, between $17 and $19 per horse power, according to the quantity and character of service rendered. On the Canadian side, when the Canadian power plants are compelled to abandon their existing fractional head plants, as they must eventually do in their own interest, their busbar costs will be in excess of $20 per horse power, when all of the charges are in. Any proposals to develop power from the St. Lawrence must take into consideration power prices at Niagara Falls, as to be financed by private capital they must be able to show that St. Lawrence energy compares favorably with Niagara Falls costs, failing in which the project would not attract investment.

The power costs just mentioned bring us now to the all-important question of what percentage of the total cost of the reconstruction of the St. Lawrence River should be charged to power, and what percentage should be charged to navigation. My figures show that according to present day costs of material and labor, and overflowed lands, this ratio should be approximately 75 per cent charged to power, and 25 per cent charged to navigation. If more than 75 per cent is charged to power, the resulting costs will not enable us to compete with Niagara Falls, and thus finance the project. If less than 75 per cent is charged to power, the load on navigation would be more than the traffic can sensibly bear. If the 75-25 ratio is accomplished, it is my opinion that the final cost for energy at generating station busbars will be approximately $17 per horse power exclusive of federal and state taxes. This price of $17 will be guaranteed to the public in advance, and thus save the public from the punishment experienced in the past through overruns in construction costs.

At a juncture when America is in sore need of every economy human ingenuity can devise, is it not most remarkable that we find ourselves, because of many changes in an art not yet forty years old, brought face to face with these unexpected possibilities from the St. Lawrence River?

It is indeed notable that in a stretch of the St. Lawrence River, the average total drop of which is only a foot and seven-tenths to the mile, 5,400,000 horse power can be built which can compete on a par with the greatest water power on the American continent, if not in the world.

We have heard much in recent years about the savings which can be secured to the public by installing great superpower systems, at costs running into the hundreds of millions. These proposals read fairly well, and are attractive to the imagination, and will, I believe, some day be carried out but the raising of these hundreds of millions will be found extraordinarily

The Wrong Way to Handle Ice.

Fig. 7

Figs. 7, 8, 9 and 10 tell their own story. The Toronto Power Company plant is successful and the Canadian Niagara power plant is unsuccessful in handling ice because the Toronto Power Company plant takes its power waters at an angle of 90 degrees with the outside waters that carry the ice, and the attending fact that the average velocities toward the turbines are always less than the velocities carrying the ice. Ice always follows the higher velocity and can not be diverted from the tendency by booms set an appreciable angle from the natural general outside ice direction. Fig. 10 shows the parallel positions of the submerged arches with respect to the ice laden outside waters in the Toronto Power Company plant (called Electrical Development Company on this drawing), and shows the submerged arches of the Canadian Niagara Power Company and their angularity with respect to the ice laden outside water. When the ice is called upon to hit such a submerged boom, as is the case with the Canadian Power Company intake, a sufficient amount of ice passes under the boom to cause the showing in Fig. 7.

Fig. 8

The Right Way to Handle Ice

Fig. 9

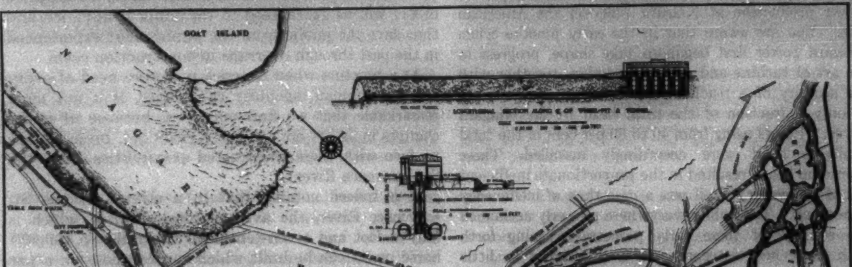
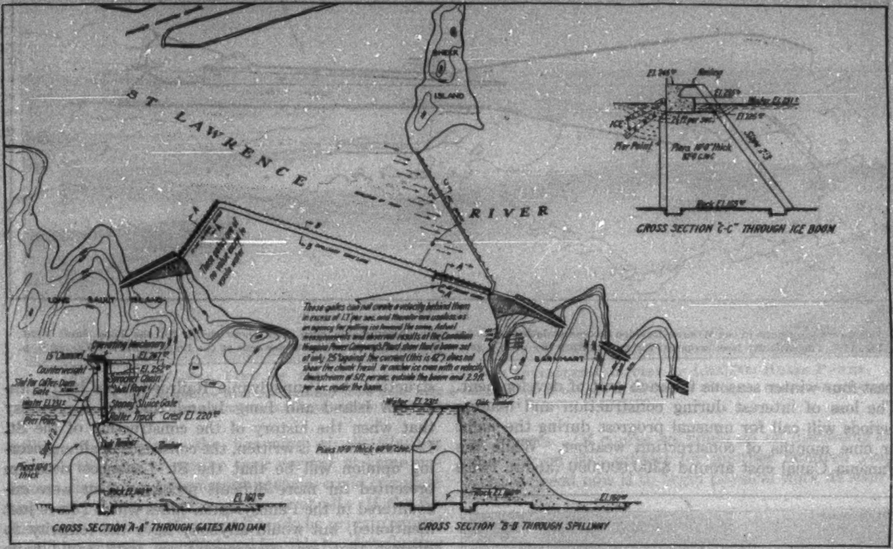

GOAT ISLAND
NIAGARA
RIVER
LONGITUDINAL SECTION
DUFFERIN ISLANDS
QUEEN VICTORIA NIAGARA FALLS PARK

Fig. 10

difficult. The superpower plans will need every big talking point which can honestly be brought to bear upon the subject, and it is my opinion that no great aggregation of money can be secured for steam installations and busbar trunk lines in these new superpower zones until the greater part of the available water power is developed and available as the vertebrae for the superpower zones. Engineers and financiers are not going to assume the responsibilities incident to hundreds of millions in trunk transmission lines and great central stations until the water power competition and capacities are known and ready to become properly the foundation for the big project.

I should like now to give you some very distinct reasons why, in my opinion, the St. Lawrence River must eventually be reconstructed by private capital. My first reason is that governments cannot and private capital can purchase and direct the engineering and construction ability which will be required to reconstruct the St. Lawrence. The engineering and construction ability required for the St. Lawrence work is far greater than that required for any previous construction in the history of engineering. Cofferdams of unprecedented size must be constructed on river beds when more than 200,000 cu. ft. per sec. are flowing, and this quantity of water alone is about five times the maxi-


ST. LAWRENCE
RIVER
SHEEK ISLAND
LONG SAULT ISLAND
BARNHART
Operating Machinery
15" Channel
El. 267
Counterweight
El. 252
Sprocket Chain
Slot for Coffer-Dam Gate
Steel Rope
Water El. 231
Stoney Sluice Gate
Pier Point
Roller Track
Crest El. 220
Oak Timber
Timber
Piers 10'0" thick
Rock El. 140
El. 160
Water El. 231
Piers 10'0" thick 60'0" c.to c.
Rock El. 140
El. 160
El. 245
Railing
El. 235
Water El. 231
Ice
2.1 ft. per sec.
El. 225
Pier Point
Piers 10'0" thick 82'0 C.to C.
Slope 2/3
Rock El. 165
CROSS SECTION "A-A" THROUGH GATES AND DAM
CROSS SECTION "B-B" THROUGH SPILLWAY
CROSS SECTION "C-C" THROUGH ICE BOOM

These gates can not create a velocity behind them in excess of 1.1' per sec. and therefore are useless as an agency for pulling ice toward the same. Actual measurements and observed results at the Canadian Niagara Power Company's Plant show that a boom set at only 25° against the current (this is 42°) does not shear the chunk frazil or anchor ice even with a velocity downstream of 5 ft. per sec. outside the boom and 2.9 ft. per sec. under the boom.

Fig. 11

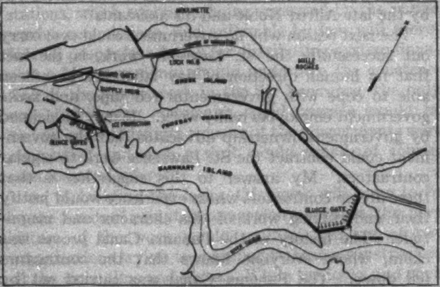

MOULINETTE
MILLE ROCHES
SHEEK ISLAND
SLUICE GATES
ICE PASSAGE
BARNHART ISLAND
SLUICE GATE

Fig. 12

Figs. 11 and 12 show the manner of handling 675,000 tons of ice per hour recommended by the Wooten-Bowden report. The reasons why this recommended plan would fail are set forth on these drawings. In times of ice movement over 60 per cent of the 1,768,000 horse power would have to be shut down until the ice movement was completed. This shut-down would vary from one day to fifteen days which would be fatal for general power distribution, but would not of course be so serious if the current were used locally for chemistry.

mum previously achieved. In all previous construction it has been possible to install cofferdams during low periods of flow, but no such low periods exist in the St. Lawrence. As you have seen, ice conditions of extraordinary severity must be overcome through at least four winter seasons for each unit of development. The loss of interest during construction and loading periods will call for unusual progress during the eight or nine months of construction weather. While the Panama Canal cost around $300,000,000 (about twice the official original estimate), this great cost was represented by work which was extraordinarily easy of construction; it was merely a matter of quantity. On the St. Lawrence we have engineering difficulties to which only the tubes under the East and North Rivers in New York are comparable. Speaking of engineering difficulties, it is my opinion, and the opinion of many engineers of my acquaintance, that the greatest engineering work ever accomplished, from the viewpoint of difficulties overcome, was the work of constructing the Pennsylvania Railroad tubes into Manhattan Island and Long Island, and yet I prophesy that when the history of the construction of the St. Lawrence work is written, the consensus of all engineering opinion will be that the St. Lawrence situation presented far more difficult problems than were encountered in the Pennsylvania tubes which I have just mentioned, but would anybody have the temerity to suggest that any government on earth could have carried out the tube construction as it was carried out by the late Alfred Noble and his assistants?

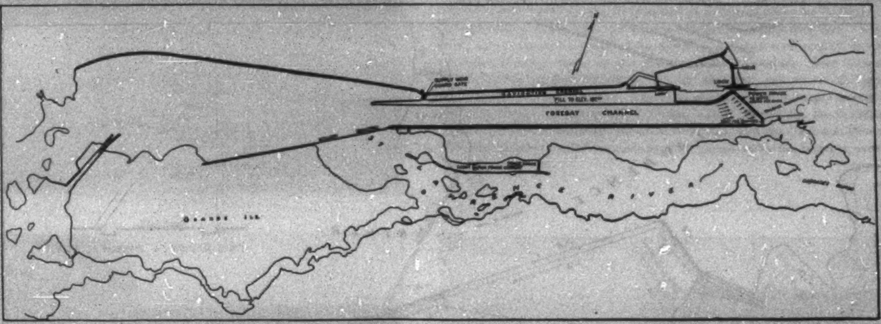


FIG. 13

This shows provisions in the Wooten-Bowden recommendations that are more objectionable even than those shown for the Long Sault plant, Fig. 11. The capacity here proposed for interruption (by even a greater percentage than the 60 per cent at the Long Sault) is 1,920,000 h. p.

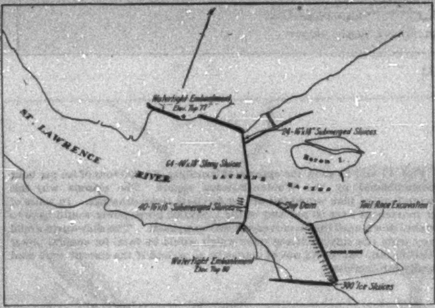

Watertight Embankment Elev. Top 77
24-16'x18" Submerged Sluices
ST. LAWRENCE
RIVER
64-40'x18' Stony Sluices
LACHINE
RAPIDS
Heron I.
40-16'x16" Submerged Sluices
Dry Dam
Tail Race Excavation
Watertight Embankment Elev. Top 80
300' Ice Sluices

FIG. 14—PROPOSED INSTALLATION AT FOOT OF LACHINE RAPIDS RECOMMENDED BY WOOTEN-BOWDEN REPORT

Capacity, 787,000 h. p.

Only a small percentage of this plant (not exceeding 15 per cent) could be operated when Lake Ontario and the St. Lawrence River ice is moving out.

The next reason why no government could ever carry out successfully the St. Lawrence work, is the fact that no human direction of day labor has ever been able to cope with governmental red tape, and make government employees really work. It may be claimed by government ownership advocates that the government could contract the St. Lawrence work to regular contractors. My answer to this suggestion is that there are no contractors whose experience would justify their undertaking work of this character and magnitude. The history of the Panama Canal proves this claim, where everyone knows that the contractors fell down. The Panama Canal was carried out by able American engineers from private walks of life, under the able management of General Goethals; but because the difficulties on the St. Lawrence are so much greater than at Panama, the Panama method of construction would fail on the St. Lawrence.

Another great reason why the power side of the St. Lawrence could not be handled by government agencies lies in the fact that coincident with the construction of the generating stations on the St. Lawrence, there must be constructed vast distributing systems, by private capital, for the use of the energy when it is ready for delivery. The private capital for these distributing systems will not, in my judgment, be found willing to undertake the financing of distributing systems that are to receive their current at some unknown time when government agencies could complete the work, if they could complete it at all. If the St. Lawrence power development is made by private capital it will be entirely practical and feasible for distributing companies to make private contracts with generating stations, which contracts, being approved by the public service commissions, and enforcible by law, will therefore be proper foundation for distributing system financing. If governments should undertake the construction of the power work in the St. Lawrence, the only way distributing companies could operate would be to wait some indefinite time until the power plants were completed, and such a wait would entail, of course, vast losses of interest.

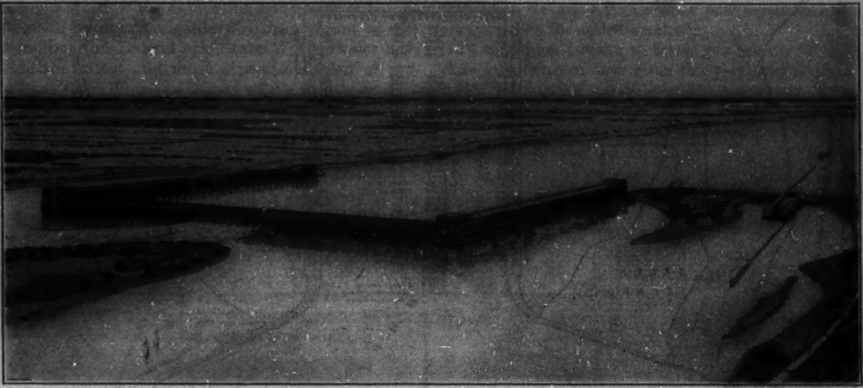


Fig. 15—Bird's-Eye View of the Cat Island Plant for Installed Capacity of 1,200,000 Horse Power

This view is a true perspective from the Canadian shore made from a complete set of borings in the bed of the river, from a complete set of mechanical drawings and from a complete set of topographical maps costing altogether in excess of $200,000.

As to building the locks, this work will have to be in the hands of private management, because the very nature of the work would prohibit the use of two organizations trying to manipulate heavy construction at the same time and place. While the locks and their appurtenant works will have to be paid for and operated by the governments, their construction by the organization which builds the power works can be arranged for on terms advantageous to the governments.

I have briefly enumerated a few of the major benefits that will result from a reconstruction of the St. Lawrence River. We are all in accord as to the value to the public of this greatest of our undeveloped resources, and of the urgency of our need of these resources. The St. Lawrence River and its Great Lakes basin have been under active official study and survey for over one hundred years, with the result that no other region of our Continent is so fully covered by general engineering reports. Of course we could go on discussing and reporting on this subject for another hundred years. What we need now is to begin physical work as soon as the best plans can be adopted. The outstanding need in American industry today is relief from present excessive federal taxation. Until this relief is felt the

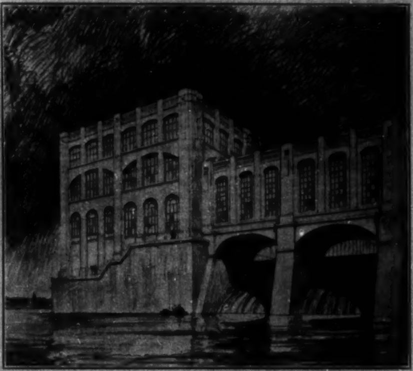


Fig. 16

Close-up perspective drawing showing two of the eighteen feet deep control gates, their gate-house superstructure and its connection to the downstream end of either the Canadian or the American power house.

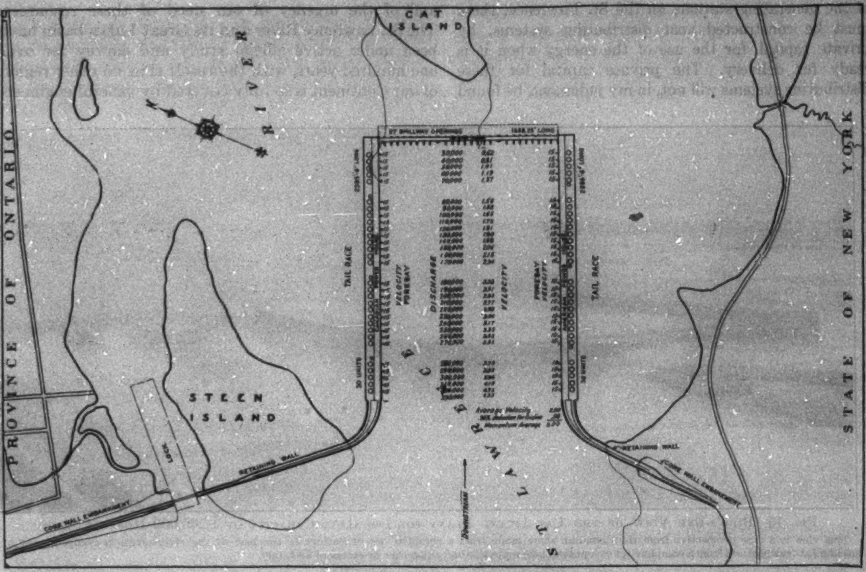

CAT ISLAND
RIVER
PROVINCE OF ONTARIO
STATE OF NEW YORK
STEEN ISLAND
LOCK
RETAINING WALL
CORE WALL EMBANKMENT
TAIL RACE
VELOCITY FOREBAY
DISCHARGE
VELOCITY
FOREBAY VELOCITY
TAIL RACE
30 UNITS
30 UNITS
ST. LAWRENCE

FIG. 17—DAM NO. 1 AT CAT ISLAND

No diversion of approaching ice from its natural direction for two miles above the control dam is required. It is disposed of through the main dam without the diversions previous experience shows conclusively must be avoided. The average velocity toward the dam is 33 1/3 per cent more than the velocity of the power waters to the wheels. This arrangement, as will be readily seen, calls for a great increase in the cost of the work because of a heavy increase in all cubitures of masonry, cofferdams and excavations. The project must stand these extra costs necessary for 100 per cent reliability or remain unconstructed. The incomplete but fairly satisfactory data in hand show that the general arrangement recommended by the Cooper plans for the Cat Island development can be installed with but little modification at Dams 2, 3, 4 and 5.

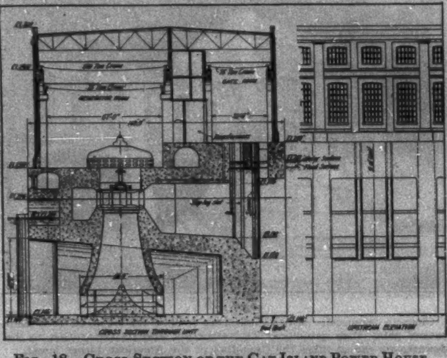

CROSS SECTION THROUGH UNIT
UPSTREAM ELEVATION

FIG. 18—CROSS-SECTION OF THE CAT ISLAND POWER HOUSE SHOWING A MAIN GENERATOR 20,000-H. P. UNIT

It will be observed that this work is standard except for the depth to foundations which is about 65 feet.

cost of living will be high, and labor and capital both must suffer. To hope that the Federal Treasury at Washington can supply for many years to come, the hundreds of millions needed for this enterprise as a governmental measure, even if its feasibility as such were unquestioned, is hoping for the unreasonable and impossible, and what of Canada and her half of the costs as a governmental measure? Canada has 9,000,000 splendid people who are today struggling with a per capita debt nearly twice our per capita debt, incurred through her wonderful loyalty to the mother country. Her casualties were 800 per cent per capita greater than ours. Canada is today struggling with an annual deficit of more than $60,000,000 in government owned and operated railroads. She must bear the burdens incident to an oversupply of hydroelectric power in Ontario, the cost of which is unnecessarily high by many millions and she has many other problems of a financial and social character, all of which she will solve in due time with great credit to herself. Because of all of the foregoing every sane, thoughtful Canadian knows that Canada cannot take on her share of the cost of the new St. Lawrence as a governmental venture for decades to come.

No, the government ownership program is not the way forward. The way forward is through encouraging private capital, properly regulated, to take up the rebuilding of the St. Lawrence along the lines the Federal Congress and the State of New York have laid out for private capital after more than ten years of continuous study of the navigation and power questions as applied to our navigable streams. I am of the opinion that the Federal and State Water Power laws provide the safest and most expeditious plan of procedure for the achievement of the new St. Lawrence. In these laws, the public interest is most fully protected. They give private initiative the fullest competitive opportunity, and thus provide maximum efficiency. If the Commissions, Federal and State, will issue the necessary St. Lawrence permits, and if Canada does her part, as I am sure she will, and finally and most important, if Canada and the United States will provide at once a high-grade permanent commission of engineers to approve the plans that are agreed upon under the operation of the permits, and to supervise construction when licenses are issued, then we will safely and speedily bid good-by to the "talk" zone, and go hopefully and confidently forward into the "work" zone of this great endeavor. No other plan, it seems to me, will ever get us anywhere for years and years to come, and if the plan I have recommended is safe and sane, why don't we get together, and pull together, and always pull in the same direction?

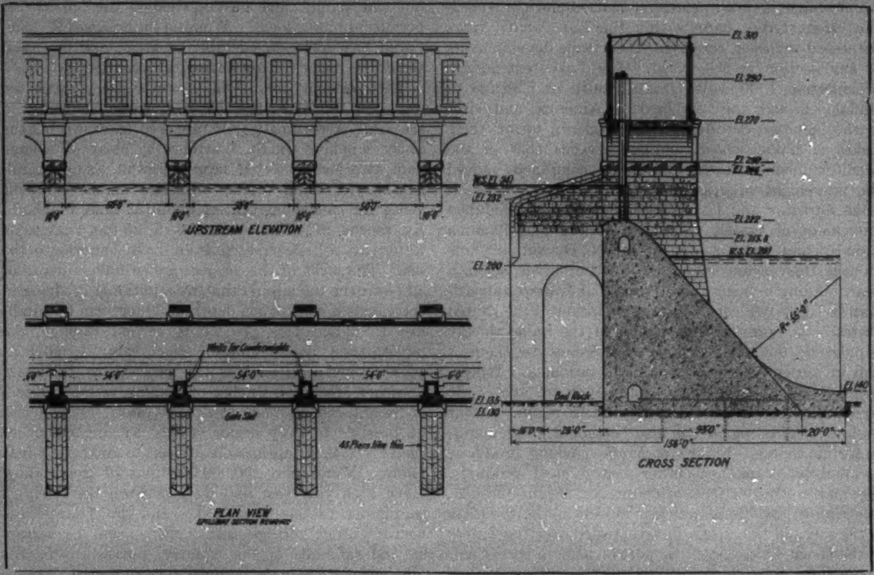


Fig. 19—Cross-Section Through the Main Dam Showing Ice Breakers 10 Feet Thick Spaced 60 Feet on Centers

Note that the large cakes of field ice approaching these ice breakers will be forced to ride up the sloping noses of the ice breakers in the usual way and thus be broken into fragments for passage through the open channels 18 feet deep immediately below the breakers, and then safely over the spillway to the pool below, from which pool the ice will be cleared by repetitions of the same process until all structures are safe. The plans here recommended will enable such a control of the St. Lawrence ice through the use of stored water from Lake Ontario as will also guarantee the City of Montreal complete immunity from the frequent ice troubles that have occurred in the past.

In conclusion I desire to thank you heartily for the close attention you have given this very brief address on what I know you will agree is a subject that will be in the minds of all of us for many years to come. I will have no pride of opinion on this subject as and when better views are advanced. The St. Lawrence enterprise is too important in its wide influence upon millions of our people to allow any mistake to be made. Its early consummation requires only the elimination of a small amount of public and private misinformation regarding it, and I predict this elimination will be accomplished much sooner than most people think.

The St. Lawrence Project

BY H. I. HARRIMAN

of Chase & Harriman, Inc., Boston, Mass.

THE great channels of trade in North America run east and west. The great river systems of the continent run north and south. There is, however, one striking exception to this general rule, where the course of the Great Lakes and the St. Lawrence breaks through the Appalachian Range, and forms a continuous waterway, 2000 miles in length, from the center of the continent to the Atlantic Ocean. Much of this water course is now open to navigation and the American Great Lakes have within the last twenty years witnessed the most remarkable maritime developments of any section in the world. The Lakes extend approximately 1000 miles from Duluth or Chicago to Buffalo through the very heart of America; and within the last two decades there has grown up on these Lakes a traffic whose tonnage exceeds that of the Mediterranean and the Black Sea combined; indeed the movement of vessels through the locks between Lake Superior and Lake Huron is twice the combined movement of vessels through the Suez and Panama Canals, and more tonnage passes Detroit in nine months than clears from New York or Liverpool in a year. Along or near these Great Lakes lives approximately forty per cent of the population of the United States. Not only are the shores of the Lakes thickly populated, but the territory contiguous to them is rich in agriculture and in mineral products. Wheat, grain, livestock, iron, coal and copper are among the great inheritance of this rich fertile region of our country. This region has also become a great manufacturing center. Flour, foodstuffs, packing products, automobiles, rails and other heavy steel products, and many other articles of commerce are produced in this region; and these articles, as well as the products of the soil and the mines, flow eastward over the waters of the Great Lakes until the port of Buffalo is reached, where they must be transferred to the rails, and move the last 500 miles of their journey to the seaboard by car rather than by boat.

Between the eastern end of Lake Erie and sea level in the St. Lawrence River, a distance of 400 miles, there are two natural obstacles which prevent navigation: first, the falls of the Niagara River; and second, the rapids of the St. Lawrence. There have for many years been shallow canals and locks around both of these obstacles, but they have accommodated vessels of such small size as to be of practically no value to commerce. In view of all these facts, it is not surprising that the people of the Middle West living near the Lakes are asking that these obstacles to commerce be removed, and that the ships of the Great Lakes be permitted to pass freely around Niagara and down the St. Lawrence to the ocean. Already the Canadian Government has undertaken the construction of an enlarged Welland Canal around Niagara Falls at the cost of about $80,000,000. This canal will, when completed, accommodate the largest lake vessel, having a capacity of approximately 15,000 dead-weight tons, or 500,000 bushels of grain. The locks of the canal will be 800 feet by 80 feet by 30 feet. The canal will initially be dredged to a depth of 25 feet, but can at any time be deepened to the full 30 feet permitted by the locks. Work on the enlarged Welland Canal has made considerable progress, and the canal should be ready for use during the year 1925.

The Welland Canal will, however, be of little use until the St. Lawrence River is made navigable to the sea. Accordingly it is proposed to drown out the upper rapids of the St. Lawrence by means of a large dam with locks, erected near Cornwall, and to parallel the two lower rapids with two canals and their locks, the canals aggregating about 33 miles in length. By means of these structures a 25-foot navigable waterway will be created from Lake Ontario to the sea. The locks of this project are to have a depth of 30 feet over the sills so that by additional dredging in the canals a continuous depth of 30 feet can be established. When this project is carried through, the largest lake vessels, some of which carry as much as 14,000 tons dead weight, can proceed to tidewater at either Montreal, Quebec or Halifax, where transfers of freight can be made to ocean vessels. It will also be possible for any ocean vessels drawing not more than 25 feet, and ultimately 30 feet, to enter the Great Lakes. More than 200,000,000 tons of freight now move each year east and west between the territory contiguous to the Great Lakes and the Atlantic seaboard. Much of this traffic always will be carried by the railroads of the country, but when the St. Lawrence Project is completed a material portion of this hugh volume of traffic will undoubtedly seek the water channel. This is conclusively proved by the tremendous growth of traffic upon the Great Lakes, which now exceeds 100,000,000 tons annually.

The opponents of the St. Lawrence Project have laid much stress upon the fact that the present channels and ports of the Great Lakes will accommodate only vessels with a draft of twenty feet or less; and that for that reason large ocean vessels cannot ply the Great Lakes until huge additional expenditures have been made upon their channels and harbors. The argument seems immaterial. As previously stated, all types of lake vessels can proceed to tidewater and there discharge their cargoes into ocean-going vessels, and there will be but one transfer and no rail haul, instead of two transfers and a rail haul as at present. If, however, there is a demand for through traffic between lake ports and foreign countries, it is entirely feasible

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Address delivered at the Spring Convention of the A. I. E. E., Chicago, Ill., April 21, 1922.

to construct ocean-going vessels of 8000-10,000—or even 12,000 tons burden of present lake draft. Such vessels of 10,000 tons burden are now in use carrying ore between Cuban ports and the Chesapeake Bay; and if the St. Lawrence Project is carried to completion, there is no question that our maritime engineers, who have so successfully designed vessels for the lake trade can also design a vessel of any desired size to ply between lake ports and ocean ports as they now exist.

The opponents of the Project have also based their opposition upon the alleged dangers of narrow and tortuous channels, of fogs and ice, and of seven-month limitation upon the use of the waterway. The St. Lawrence River will be made navigable by the construction of a large dam at the lower end of the International Section, and by two canals around the two sections of rapids that lie entirely within Canada. In the entire length of the St. Lawrence there will be but nine locks and thirty-three miles of canal navigation. For the balance of the distance navigation will be through a river as wide as the Hudson at New York City; and the entire delay incident to canal navigation in the St. Lawrence and in the Welland Canal will be less than the time required by an ordinary freighter to travel 200 miles. Fogs exist in the lower St. Lawrence; but the hydro-graphic charts of the Federal Government indicate that the fog belt between Montreal and Liverpool is of less extent than between New York and the same port. Fogs and ice have not prevented Montreal from becoming the second port of export in North America; nor has the closure during the winter season stopped navigation upon the Great Lakes or prevented the construction of the Erie Canal.

For these reasons I believe that with the opening of the St. Lawrence to navigation the Middle West will have a usable water route to tidewater over which freight can be sent at much less expense than over all-rail, or water-rail, routes now in existence. I further believe that the existence of such a water route will affect not only the rates of the grain and other freight which actually use it, but the whole rail rate structure between the Middle West and the Atlantic seaboard. This has certainly been the effect of the Panama Canal upon rail rates between Atlantic and Pacific ports.

The extent of the saving arising from water transportation cannot be definitely prophesied, but reasonably accurate conclusions can be drawn from existing rates. At present a bushel of wheat is carried from either Chicago or Duluth, 1000 miles to Buffalo, for 2 cents or less; and on the same mileage basis, with due allowance for delays in canals and locks 3 or 3½ cents would be a fair rate to Montreal. The lowest rate at which grain can now be carried from the West to tidewater is 2 cents to Buffalo, and 12 cents from Buffalo to New York or Boston—a total of 14 cents. This shows a saving to tidewater of at least 10 cents per bushel *via* the St. Lawrence route; and as New York and Montreal are equally distant from Liverpool, it would mean an equal saving on the through rate. What holds true of grain will also hold true of many other western products destined for European ports.

I also believe the St. Lawrence route will favorably affect the transportation costs between the Middle West and the Atlantic Coast ports. The rail rate for the entire country is now approximately 12.1 mills per ton-mile. If coal is excluded this average rate rises to 15 mills. Water rates on the Great Lakes average less than 1 mill per ton-mile; and on the ocean vary according to the class of freight from 1 to 3 mills. Probably 2 mills per ton-mile is a fair water rate to compare with an average rail rate of 15 mills.

From Chicago to Boston the rail distance is 1034 miles as against 2682 by water. From Duluth the relative distances are 1513 as against 2775; and taking into account relative rail and water rates and relative distances, it would seem that a ton of freight is now hauled by rail from Chicago to Boston for $15.51, as against an estimated charge of $5.36 by the water route. The corresponding rail rate for Duluth is $22.70 as against an estimated cost of $5.55 by water.

Figures based on averages may not be exact, but they do indicate tendencies; and they certainly give assurances that freight can be carried from the Middle West to Atlantic ports by water much cheaper than by rail.

It is a well recognized economic principle that the price of any commodity in universal use is determined by the price at which the surplus of that product must be sold. The surplus grain of the world is sold in Liverpool. To this market is shipped the surplus grain from the United States, Canada, Argentine, Russia, and Australia; and there in competition the world price of grain is established, this price governing not only the grain sold in the Liverpool market but the grain sold in the producing countries. The price in the producing country is therefore the world price set in the Liverpool market less the cost of transportation between the farm and the English Channel; and the American farmer receives each year for his grain the Liverpool price less the freight to Liverpool. If therefore, it is possible to reduce the freight charge by 10 cents per bushel, the farmer will receive 10 cents per bushel more for his entire crop. This would mean over $350,000,000 per year to the farmers of the country. Every other grain producing region of the world which has a surplus lies within 250 miles of navigation. Our grain region lies from 1000 to 1200 miles from the coast; and this great handicap upon our western farmers is the great reason for their insistence to (use the words of the President) that "the salted and unsalted seas be connected by a suitable channel."

By act of the American and Canadian Governments, a Joint Commission of the two nations has been investigating the feasibility and cost of the project. This Commission has recently submitted its report to the two Governments, and its findings are that the project is feasible, desirable, and reasonable in cost. The estimates of cost were made by Government engineers of the two nations after an examination extending over a year's period. These engineers estimate the cost of the entire project at $252,000,000, this estimate including the cost of producing 1,464,000 horse power of continuous energy. The figures were based upon 1920 costs—as an example, concrete is estimated at $12.00 per yard. It is further the express belief of the engineers that the figures of cost are conservative and that due allowance has been made for the inevitable contingencies of a project of this size.

Mr. Hugh Cooper, an eminent hydraulic engineer, who has made extensive studies of the St. Lawrence River, believes that the plan proposed by the Government engineers is impracticable, that their estimates of cost are inadequate, and that their scheme is wasteful of the potential energy of the stream. Cooper proposes a different plan which, at a cost of about $300,000,000 for the International section, will make that section navigable and develop about 2,400,000 horse power. To this $300,000,000 must be added about $100,000,000 for the canals around the lower rapids, in order to make the entire river navigable. The total cost of his project is therefore approximately $400,000,000 as against $252,000,000 for the plan of the Government engineers.

The criticisms of Mr. Cooper should be given most careful consideration in the preparation of the final plans. In my opinion, however, the vital fact is that both the Government engineers and Mr. Cooper agree that it is entirely feasible to improve and make navigable the St. Lawrence River, and to develop as an adjunct thereto a huge block of reliable electric energy; and while Cooper's estimates are higher than the estimates of the Government engineers, yet the amount of power which he will develop is far greater and there is really very little difference in the cost of a horse power as developed by one or the other plan.

The value of the power which will be produced on the International section will largely offset the annual cost of the project. Based upon a cost of $252,000,000 the interest charges, sinking fund requirements, and operating expenses of the project, if carried through by the Government, should not exceed $17,000,000 per annum. If the entire annual cost of the project is charged against the power development (and I do not advocate this) it means an annual switchboard cost of from $11.00 to $12.00 per horse power. This is equivalent to a kilowatt hour cost of from 2 to 4 mills depending upon the load factor at which the energy is taken. To this switchboard charge must be added the transmission costs from the St. Lawrence River to the great markets of New England and New York; but after making such allowance it is certain that, according to either plan, energy can be laid down at great central substations in New England and New York at well under 10 mills per kilowatt-hour.

I do not feel that the entire cost of the project should be charged against power. The figures cited are however based upon the entire charge of the project being carried by the power developed; but it may well be argued that navigation should pay a portion of the cost, thus enabling power to be sold at lower rates than above indicated. I, however, wish to point out that the market is ample to absorb all of the power which can be generated; and that the energy will be exceedingly cheap even if power carries all of the charges. Within a reasonable time after the St. Lawrence is open to navigation, it can be made a self-supporting project, and would be well warranted merely as a plan for the development of energy.

The Western proponents of the Great Lakes project have assumed that the project would be carried through in its entirety by the Governments of the two nations, and I have thus far discussed the proposition from that standpoint. A statement, has however, recently been made by gentlemen connected with large financial interests that a group of American financiers are prepared to construct two dams along the International section which would develop nearly 2,000,000 h. p., and whose construction would also drown out the rapids of the international section of the river and by the construction of locks in the two dams (to be paid for by the two Governments) make the river navigable from Lake Ontario to Lake St. Francis.

If such an arrangement can be worked out, it should be given most careful consideration, as the task left to the two governments would be merely the construction of the lower canals with their locks. Under such a plan the government expenditures would probably be less than $100,000,000. Furthermore, it would remove the governments from any connection with the development of hydroelectric energy and leave that business to private enterprise,—a most desirable outcome, if feasible.

My own feeling is that the two great features of the project—continuous navigation from the Great Lakes to the sea, and cheap hydroelectric power—must both be carried out. No plan must be adopted which gives one without the other, or which delays one at the expense of the other. With these fundamental facts in view the more that can be done by private enterprise and the less by the two Governments, the better it is.

Some opponents of the project claim that it will work great injury to the railroads of the country, and tend to increase existing freight rates. Such opponents fail to take into account the tremendous growth of the traffic of the nation. In 1890 the railroad tonnage of the country amounted to 79,000,000,000 ton-miles; in 1900 it had risen to 141,000,000,000 ton-miles; by

1905 it had increased to 187,000,000,000; and in 1921 exceeded 448,000,000,000 ton-miles. This shows a steady increase of approximately 100% in each decade; and would indicate a tonnage of 800,000,000,000 ton-miles by the time the St. Lawrence project becomes an actuality. I remember the frightful congestion of traffic in 1918, and am appalled at considering the expenditures which must be made to handle the inevitable traffic of 1930. At present the population tributary to the Great Lakes is 40,000,000. Twenty-five years from now it may well be 75,000,000; and the requirements of the growing traffic of the country, and of its growing population will demand the use of every possible avenue of transportation. I therefore feel that the development of water transportation from the center of the continent to seaboard will be of immense advantage to the railroads, greatly reducing the investments they must make, and enabling their existing rails to be used for local and high-class tonnage. The following quotations from a recent address of Mr. Elisha Lee, Vice-President of the Pennsylvania Railroad, are of great interest. He says:

> Traffic on our American railroads measured in ton-miles doubles about once in a decade. This rate of increase has been maintained for at least two generations with surprising regularity, despite the varying cycles of booms, panics and depressions through which the country has passed meanwhile.
>
> The next time our country has a real revival of business we shall in all probability be confronted with the most severe congestion of railroad traffic, and the greatest inadequacy of railroad facilities, ever experienced in our history. When that happens rates will be lost sight of. Every one will be clamoring for service. Nothing could more quickly check a wave of prosperity than the inability of our railroad facilities to handle the traffic which good times will create.
>
> I am firmly convinced that we face such a condition with almost absolute certainty in the not remote future.

One more objection remains to be considered, namely; the sentimental objection of the investment of American money in Canadian territory. In this connection, however, it should be remembered that by treaty the Great Lakes and the St. Lawrence for their entire length are open to the equal use of the nationals of both countries. Since the war of 1812 the lakes and the river have been recognized as the joint artery of the two governments. Our use of the St. Lawrence because of our greater population, and industry, will greatly exceed the use of Canada; and there is certainly no sound reason why we should not bear our proportion of the expense irrespective of its location. It should be noted further that each nation is to pay the entire expense of its own power developments; and that expenses are shared only as they refer to navigation. Canada owns the Grand Trunk Railroad, and thus has an investment in the United States of over $200,000,000 and if Canada has not hestitated to invest in railroads partially within the United States, certainly we should not hesitate to invest in a joint waterway more beneficial to us than to our neighbor. If the United States and Canada jointly develop this great route of trade, it will tend to cement the ties of industrial and political friendship which have existed between the two countries for over a century.

Thus far I have considered the St. Lawrence Project from its effect upon the nation as a whole; and my conclusions are that it will greatly benefit the commerce and industry of the country.

Let us turn now to the consideration of the immediate effect of the project upon our own state and upon the Port of Boston. Commercially, it will give us a direct water route between the Middle West and our own ports. It will also bring lake traffic to the terminals of our New England railroads at Ogdensburg and Montreal, and thus reduce the distance to lake navigation from 500 miles at Buffalo to 250 miles at the St. Lawrence. Our traffic will also be free from the crowded gateways at Albany and Buffalo; and our own railroads through their own or affiliated boat lines will reach all of the great ports of the West. The existence of such a route will also help us to maintain our present differential rates which have been so great an asset to New England's industries. Finally, it will give us a definite and compelling reason for the abolition of the rail differential which now exists in favor of Philadelphia and Baltimore.

The project will also give to New England a supply of cheap energy nearly sufficient to operate its railroads, its utilities, and its industries. Previously in this report we have discussed the cost of power generated on the St. Lawrence. Suffice it to repeat at this time that power can be generated on the St. Lawrence and transmitted throughout New England at a cost less than the cost of power made by coal at the mouth of the mine in Pennsylvania. Not least among the advantages of the hydroelectric power of the St. Lawrence is the fact that it will tend to grow cheaper with increased use, whereas power generated by coal is bound to increase in cost with the growing scarcity of fuel. Finally, our power supply will be free from the embargo and the delay at the crowded railroad gateway. The industry of New England needs for its continued maintenance and prosperity efficient and cheap transportation and low-priced power. Both of these will be supplied when the St. Lawrence is open to navigation and its power made available for use.

New England's chief argument against the opening of the St. Lawrence has been its fear that the foreign commerce of the Port of Boston would be seriously affected. This objection is worthy of every consideration. No positive prediction can be made as to the beneficial or harmful effect on Boston's foreign commerce. The arguments which have been presented show great possibilities for good as well as harm. Boston's foreign commerce has for the last twenty years steadily declined, until it has reached the lowest point in its history. This has been due largely to the operation of the rail differentials in favor of South Atlantic Ports, which have diverted from Boston the grain and other heavy commodities required in a properly balanced cargo. Last year Boston's exports of grain were only about 4,000,000 bushels out of a total of 300,000,000 for the entire country and Canada. If the St. Lawrence route is opened, much grain will be brought to river ports in lake vessels and stored in elevators for export purposes. Much of this grain will go abroad directly by water from Montreal; but it is also true that much of the stored grain will come to Boston and Portland, particularly during the five months when the St. Lawrence is closed, and thus furfurnish Boston the bulk cargo which her foreign commerce requires. It must also be of great advantage to New England ports to have the tonnage of the Great Lakes brought within 250 miles of its ports and in direct touch with its own rail heads on the St. Lawrence; and New England's railroads whose interests are identical with the interests of the Port of Boston, will have every incentive to make rates which will bring the lake commerce to Boston. Mr. A. H. Ritter, of the Department of Commerce, has very clearly brought out the fact that Boston has a large inbound commerce, and is particularly in need of export products, in order that ships may have both inward and outward cargoes. He also points out that Montreal has very little inbound commerce, and that a vessel could better afford to come loaded to Boston and pay the rail haul from Ogdensburg or Montreal to Boston for export cargoes, rather than to go to Montreal empty and effect the saving of the rail haul.

It should also be remembered that the value of any port is measured by its service to domestic as well as foreign commerce, and no one can doubt that a large amount of domestic commerce will flow by water from the Port of Boston to the ports of the Great Lakes. While, therefore, there is a possibility that some of the commerce of the West now flowing through New York and Boston will flow directly to Europe via the St. Lawrence, yet, so far as Boston is concerned, there is every probability that through this route she will gain the bulk cargo, at least during the winter season, which her foreign commerce now lacks.

Various other local objections have been raised. For instance, Montreal fears that freight will pass by it and that it will become a way-station on the St. Lawrence. Portland is apprehensive lest it lose some of the grain which the Grand Trunk now ships through that harbor when the St. Lawrence is closed. Buffalo fears that it will lose the transfer charges now paid at that port; and New York State fears that the Erie Canal will receive less traffic.

All of these local objections must be given due consideration. I think, however, it can be assumed that no local consideration should stand in the way of a great economic development which will benefit much of the country; and Montreal, Portland, Buffalo, or New York cannot permanently expect to receive a toll for their individual benefit that increases the cost of moving the exports or imports of the world to and from the West, or that denies to New England a much needed supply of cheap power. The weavers of Lancashire objected to the introduction of the power loom because they feared it would deprive them of their livelihood, but the power loom made Manchester. So these local losses will be more than made up by resulting benefits which cannot now be foreseen.

In my opinion, New England and New York have more to gain from this project than even the States of the West which are now so actively supporting it. When men like President Harding and Secretary Hoover advocate this project as one of the greatest constructive engineering projects of this generation, and say it is a development equal in its importance to the Suez or Panama Canals, all must admit that it is of great national, as well as local significance.

The people living in the region of the Great Lakes are in the same position as the people residing along the shores of the Mediterranean would be if the Straits of Gibraltar were closed, or the nations bordering upon the Black Sea if the Dardanelles were obstructed by impassable rapids.

At present the great demand for the improvement of the St. Lawrence comes from the merchant, the manufacturer, and the farmer of the Middle West and the Northwest, and from Canada, who demand that the traffic of the Great Lakes have direct access to the sea; but when the citizens of New England and New York appreciate what the project really means to their industries and to their railroads, they will be equally insistent that the St. Lawrence be opened to world commerce and its power made available for the use of mankind.

I cannot better close than by quoting the words of President Harding in his address to the National Agricultural conference held in Washington on January 23d. He said:

> I have spoken of the advantage which Europe enjoys because of its easy access to the sea, the cheapest and surest transportation facility. In our own country is presented one of the world's most attractive opportunities for extension of the seaways many hundred miles inland. The heart of the continent, with its vast resources in both agriculture and industry, would be brought in communication with all the ocean routes by the execution of the St. Lawrence waterway project. To enable ocean-going vessels to have access to all the ports of the Great Lakes would have a most stimulating effect upon the industrial life of the continent's interior. The feasibility of the project is unquestioned, and its cost, compared with some other great engineering works would be small. Disorganized and prostrate, the nations of central Europe are even now setting their hands to the development of a great continental waterway, which, connecting the Rhine and Danube, will bring water transportation from the Black to the North Sea, from Mediterranean to Baltic. If nationalist prejudices and economic difficulties can be overcome by Europe, they certainly should not be formidable obstacles to an achievement, less expensive, and giving promise of yet greater advantages to the peoples of North America. Not only would the cost of transportation be greatly reduced, but a vast population would be brought overnight into immediate touch with the markets of the entire world.

Another View of the St. Lawrence Project

BY S. WALLACE DEMPSEY

House of Representatives, Washington, D. C. Chairman of the Committee on Rivers and Harbors

THE question as to whether the United States shall help Canada defray the expense of improving the St. Lawrence river, as Mr. Cooper said, is a great question. It is one that involves an enormous amount of money and it would take, the engineers estimate, at least ten years to do the work. So we should know well before we begin what the problem is, what it promises, how it compares with other things. It is a great transportation problem. Primarily at the base of it is the question of transportation. Water power is purely incidental.

I am to talk to you as to how this question presents itself from the standpoint of the United States. Well, we are just at the end of a great war. For the first time in the history of the country we are groaning under the burden of an enormous debt. Every question of Government activity has to be met from that angle and I am going to illustrate it to you. The city of Chicago has furnished a very able man as the first director of the budget, General Dawes,—a man of action, a man of brains. When he provided in the first budget that was ever presented to a Congress of the United States for the expenditure for all our rivers and harbors, how much do you think he estimated? We have been talking about one half a billion or 500,000,000 dollars as the cost of the development in the international section of the St. Lawrence. And on the 50 per cent basis, one half of that would be 250,000,000 dollars. But it is not the 50 per cent basis at all, that is proposed by the Joint Commission organized by Canada and the United States to study and report on the St. Lawrence route and what we are considering today is what the Joint Commission recommends. They have been asked to investigate and to report upon this subject and we are proposing to act on their report. They do not propose that the United States shall bear one half of the expense of this great undertaking. They say that the disproportion in wealth, in population, in commerce, between the United States and Canada shall disappear, that we shall bear—the two countries shall bear,—that expense in proportion to population, wealth and commerce, and that means, as you all know, that the United States shall bear nine-tenths of the cost. And we don't stop there. A great canal has already been dug, the Welland Canal. It is practically completed. Its expense has been borne by the Dominion of Canada and this Joint Commission proposes that the United States shall share in the same proportion the cost of that canal.

We have done the work of improving the Great Lakes. We have dug the canals, we have improved the harbors, we have done all the work that leads to their enormous commerce, the cheapest commerce in the world that floats down from Duluth all the way to Buffalo. And if we should pay nine-tenths of the cost of this canal, which Canada has already constructed, why shouldn't Canada come over and bear its proportion of the cost of this work which we have done for many, many years and which we are still doing?

When as I say, General Dawes began to consider what he would allow to the United States for all of its rivers and harbors in this great country of ours, with about five thousand miles of sea and gulf coast, with 25,000 miles of navigable rivers, with 25,000 more that can be made navigable, how much money, as against nine-tenths of somewhere from 500,000,000 to a billion and a half, which is proposed for this one route, how much do you suppose the General expected to allow us for all of this commerce within our country? Thirteen millions of dollars. And that is all he thought that the present conditions of this country could allow, with its burden of taxation, with the people paying high prices, as Mr. Cooper says, for labor and for supplies, and for materials.

The Committee on Rivers and Harbors convinced him that he was wrong, convinced General Lord, the Finance Officer of the War Department, convinced Secretary Weeks that he was wrong, and as a result they consented to 27,000,000 dollars. At that time we expected 15,000,000 dollars could be used from unexpended balances to the credit of River and Harbor projects, and it turned out that there weren't unexpended balances available. So we went on the floor of the House and we had to make a fight and a strenuous fight, and a fight for which we had to prepare for four or five weeks, in order to enable us to get an additional 15,000,000 dollars for our rivers and harbors.

What was the condition of our rivers and harbors? Why did we need this money? We needed it for two reasons. First, during the war not a dollar's worth of work was done upon any river or harbor in the United States, for the Secretary of War must have certified that it was necessary to win the war. Since it could not come within that definition the harbors were allowed to silt and fill up. And let me give you an illustration. Down in Mobile we adopted a project for deepening the harbor thirty feet, many years ago, and today the harbor in Mobile has less draft than it had when we adopted the project and what is true of Mobile is true generally of the rivers and harbors in the United States, they have been going backward instead of forward ever since the war broke out.

In addition to that this country is growing very rapidly and we need to use all of our transportation facilities, and keep furnishing and supplying new ones from time to time to meet the constantly increasing and multiplying demands of commerce. And on that

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account it is necessary that we should have our rivers and harbors used to their maximum.

One other thing. Owing to the way that the railroads were managed during Government control, owing to the fact that their operation became enormously more expensive, owing to the fact that freight rates in consequence have soared to an unheard of level, the only relief in sight was by cheap transportation by water, and how could we have it unless we improved our waterways? And then we had living examples of the fact that it was important to improve our waterways. All we had to do was to look to the south of us and we found on the Mississippi River that under Government management, which is always wasteful, always inefficient, we found that in spite of that Government boats are being operated there under Government control, and with all of the wastefulness, with all of the extravagance, with all of the inefficiency of Government operation those boats are paying, taking into account every kind of an overhead charge which it is possible to put into the account against them.

How has it come about that this traffic upon the Mississippi, for the first time in the history of the stream, is really profitable? In a very natural way. In the olden days they used to fit out a barge on the Ohio River and they would send it down the Ohio and down the Mississippi and when it reached New Orleans they would break it up and sell it for firewood. Why? Because they couldn't get a return cargo and it cost more to take it back up the river unloaded than it would cost to build a new raft up on the Ohio. And for the first time in the history of the Mississippi they have found that they can get return cargoes to the full capacity of all the boats, and that is what has made the navigation of the Mississippi profitable, in spite of the drawbacks to which I have referred.

That is only one example of the use to which we can put our waterways and of the necessity of using them. So here we are, from the Governmental standpoint in this position, of needing great sums of money to improve our own waterways in a time when we owe a huge debt and must economize, and we want to examine the whole thing carefully and fairly. We are all Americans, we all have the interests of the whole country at heart. If it is the best thing to build this waterway we want to build it, but we don't want to decide it as a matter of sentiment, we don't care to decide it as a matter of feeling, we want to examine it soberly as we would examine any other business question in the light of the facts, and see whether it will bear such an examination.

We find that it is well nigh impossible to get what our own waterways need as a sheer and dire necessity, we find as we look back over the history of the past twenty years that we have only had about 30,000,000 dollars a year for all our waterways. We find that last year we spent 40,000,000 dollars. We find that it is going to be necessary to spend 100,000,000 of dollars a year on the waterways in the United States to develop and maintain them. And yet as I say, those in charge start off by offering us 13,000,000 dollars to meet a necessity that requires 100,000,000 dollars.

In the face of facts like these, should we not examine a proposal to spend hundreds of millions of dollars on one waterway traversing a foreign country? Isn't that fair, that we should examine it closely, that we should scan it, that we should be entirely satisfied before we reach a conclusion?

Let us take the report of the Joint Engineers, first of all, and see, because that is what we have before us, what they propose. They say that we are to have a channel of 25 feet through the St. Lawrence, and then say we are to be satisfied with the channels in the Great Lakes, except that in the pivotal harbors and through some of the channels we may get an increased depth from 20 to 21, 22 or 25 feet, which are the controlling depths today. What is the situation as to that depth? Is that depth sufficient for the purpose for which it is intended? Is it going to enable ocean going vessels to traverse the St. Lawrence route,—ocean going vessels of a size that can compete with the lake freighters that now carry the traffic of the lakes? We have on the Great Lakes today freighters carrying 14,000 tons, and everyone knows that is the cheapest transportaion anywhere in the world. These great freighters are practically square boxes which require scarcely any space for coal, they are loaded and unloaded in an incredibly short space of time and owing to the fact that they don't need the reserve space, that loading and unloading is so very cheap, that the cost of construction is very low, transportation on the Lakes is, for its cheapness the marvel of the world.

I don't know myself the comparative average costs of transportation on the Great Lakes and of that on the ocean. I recently had the pleasure of having a joint debate with Senator Ransdell of Louisiana, an ardent advocate of the St. Lawrence route, at Boston, when Mr. Harriman, who is to follow me, was present and in that debate Senator Ransdell made the statement that the average cost of transportation per ton per mile on the ocean was three mills, and that the average cost on the Great Lakes was one mill. Now I know nothing about the accuracy of his figures, but I am reliably advised that the cost of transportation on the ocean is much greater than the cost on the Great Lakes. So starting with that as a basis, I ask how you can, for the purpose of economy, substitute ocean navigation, which is far more expensive than navigation on the Great Lakes, for shipment by lake freighters and yet cheapen the cost of transportation to the wheat grower of the northwest? You start with that as your primary proposition and then you come to examine the details, and see whether it is simply the average cost of transportation on the Great Lakes and of transportation on the ocean, that you have to meet, or whether there are other factors that enter into the problem and make it more clear still that you cannot compete by an ocean going boat with the cost of transportation which is established today by the lake freighter. What kind of ocean going boats, what capacity of ocean going boats will be able to traverse the Great Lakes? That is your first problem. Here you have a depth, a controlling depth of 20 to 22 feet, because your boat must be able to traverse the very shallowest section. The steamship companies say that the largest sized boat, that could traverse the Great Lakes and its channels and harbors, would be one of 4000 tons capacity, and they would have to compete on the Great Lakes with these freighters carrying 14,000 tons. What would the result be? You wouldn't have the ordinary competition between the cost on the ocean and the cost on the Lakes, but you would have in addition to that, not a competition between two boats, one an ocean boat carrying 14,000 tons and another a lake freighter of the same carrying capacity, but you would have this small, insignificant ocean boat, which isn't large enough to be economical on the ocean competing with a 14,000 ton lake freighter, 4000 tons is all that could be carried in an ocean ship upon the St. Lawrence route. Can there be any doubt that the 14,000 ton Lake freighter would carry freight very much more cheaply than the 4000 ton ocean ship?

Before I leave that question of depth, let us go to another demonstration of the fact that the proposed depth would be insufficient. The Joint Commission in its report says that the controlling depth from Montreal to the sea, a distance of a thousand miles, is 30 feet, but they say that that is being improved to 35 feet. What does that mean? It means that Canada and Great Britain have used that channel for ocean going vessels for a very long time and as the result of all of that experience they have found that 30 feet even isn't a sufficient depth, and that to navigate the channel economically, to get the best results, the lowest freight rates, and to make it profitable to use the channel, you must have a depth of 35 feet.

So here is the channel from Montreal to the sea, one thousand miles long and it is proposed to supplement that by a channel, from Montreal west, of twenty to twenty-two feet, and join together that mismatched, dissimilar pair and call it a joint and complete route. Of course it is utterly impossible.

What next do you find? That there isn't simply the disproportion of costs between the lake freighters and the ordinary ocean going boat, but that there is a great difference because they are built on an entirely different principle. The one is built much higher than the other, the ocean vessel having to be built for the buffetings of that enormous expanse of water. But you don't have to build simply the ordinary ocean going boat for the St. Lawrence route. The Encyclopedia Brittanica in its latest edition says that for the navigation of the St. Lawrence route you must have an especially strongly constructed vessel because of the fact that icebergs are present in that channel at all times of the year.

That adds to the overhead, and to the cost of construction; the interest charges, as Mr. Cooper pointed out, go on, and as a result, the cost of carrying the wheat, if you are going to carry it in that ocean-going vessel, is increased by the interest on that added cost of construction.

Then the Joint Commission says that it is not simply a question of fogs, tides, nor icebergs, but the combination of all of these difficulties and dangers of that route, there resulted in 1909 the adoption of what was known as the British North American Clause of Marine insurance requiring a very high marine risk rate all through the St. Lawrence. The Joint Commission in this report recommending this route says that that is a handicap to the usefulness of the route.

Those are a few of the objections to this route. Mr. Redfield, Secretary of Commerce, investigated this matter in 1918 and made a report in which he said that there never would come a time when ocean-going vessels would carry freight in the restricted channels of a canal or a river or upon the Lakes, that the over-head makes it absolutely impossible, the cost of construction, the cost of maintenance, the cost of operation was so very much greater for all boats of that description.

A report was made by the Army Engineers at about the same time, and they reached the same conclusion. I don't understand that any Board of Army Engineers has united in this report of the Joint Commission. My understanding is that a single Colonel from the United States Army was designated on our part, and an Engineer on the British side was designated, and those two engineers joined in the making of this report.

Let us take this St. Lawrence route and examine it regarding waterpower. It runs along the American border for a very short distance. In that distance there occurs one of the opportunities to create water power. Every one in the United States is in favor of the development of the water power on the St. Lawrence, on the Niagara, at every point in the United States where it can be developed. It is the one thing since I have been in Congress that has been my especial care, for which I have fought incessantly, day in and day out, ever since I have been a member of that body, because in the district, which I have the honor to represent, there is located the greatest water power in the world, the power of Niagara. We have developed a small part only of the great power there and I have seen a little village of 3000 people grow to a city of 60,000 people, (with $200,000,000 of assessed valuation), which is the greatest electrochemical center in the world, I saw there the development of more of the things that went to the successful prosecution of the war than were made at any other point in this great and rich nation of ours, with all of its broad territory. So, of course, I believe in the development of power, everywhere throughout our country. But the development of power anywhere, if the power is worth developing, doesn't have to be done at Government expense. Go down and examine the applications for the development of water power in the Federal Power Commission at Washington. Talk with the Secretary, Mr. Merril, find if there is any water power that is worth having for which there isn't an application pending. Find if there aren't competitors in each case where the power is worth anything. Find if men aren't eager, not ready, but eager and ready to advance the money at a moment's notice, the instant they can get the license. That is the situation as to the development of power.

Then if anyone says to you, "Why, you can do better by Government development than you can by private development," say to him, that he can look back to the period when the Government controlled the railroads and it had them for only 26 months under operation and say to him that during that period the Government lost the stupendous sum of one billion dollars, one twenty-sixth of its total national debt today incurred by reason of the war. And say to him that you had the poorest service during Government operation you ever had in the history of your country and if he wants a practical illustration, tell him that you couldn't trace a freight car from the time it left a yard until it reached its destination, if it ever reached it. And then tell him, if he wants a particular instance of how bad it was, to go down into New England and find their roads practically ruined and if he will examine the records he will find that during the first 18 months of Government control they earned only 15 per cent of the standard return,—of the average of their earnings for the three years preceding Government control,—and, then if he says to you, "Why, railroads are not water power, and we are talking about water power," tell him to go down to Niagara and visit both sides of the river there and then go on to Quebec and tell him he will find that on the Niagara, on the American side we furnish power 40 per cent cheaper to the consumer than they do over on the Canadian side where it is government controlled, and then tell him to step down to Quebec where it is developed by private enterprise and he will find that it is produced there 32 per cent cheaper under private enterprise than it is by the Government.

So far as the Government part of this is concerned the Government doesn't need to, and shouldn't, take any hand in the development of the power, and there isn't a man in the United States who recognizes more fully than I do, the importance of power development or who is more earnestly, in season and out of season, every day of the year, for water power development.

Let me say one word more about this question of water power. Many people say to you that water power will pay the entire cost of the improvement of the St. Lawrence. Well I say to you that as a matter of law, it can't do that and as a matter of justice and fairness it shouldn't do that. This water power will be developed under the General Water Power Bill and I had the honor personally to make the fight which kept boundary streams in the General Water Power Bill. You have the legislation ready and all you have to do is to give private capital the opportunity to develop the power.

The General Water Power Bill provides this,—and it is not going to be changed because it is a just and fair bill,—it provides that when the state where the water power is developed has a Public Service Commission, that that Public Service Commission shall regulate the charges. On what principles are they regulated? They regulate them on this basis,—they allow the companies to prove what it costs per horse power to develop the power which they are selling. They allow them a reasonable sum for depreciation and amortization and then they allow them a reasonable profit. Now how are they going to allow for something that hasn't anything to do with water power? Because navigation has no connection with water power, navigation is an entirely separate and distinct thing. How can they allow those who develop the water power to charge the consumers of the power for the development of navigation in the St. Lawrence? It can't and shouldn't be done and we shouldn't, for one moment, delude ourselves with any dream that we are going to pay the entire cost of improvement of navigation out of the development of the water power. Why, this country needs the improvement of its transportation facilities. All along the Atlantic Coast, starting in from Boston and Portland, including every southern port, Baltimore, Savannah, Charlestown, Mobile, Galveston, New Orleans, every port is growing from day to day and year to year in its commerce, and most of these ports are growing rapidly in the export of wheat.

Do you realize,—and it seems impossible for those who haven't examined it to realize it,—do you realize that on the Houston Ship Canal they are carrying 10,000,000 tons of freight a year? Of what kind? They are carrying that material which is just as useful as water power,—oil. And it is increasing in quantity from month to month and they have found down there that it is not economical to have a 25 foot water-way, on that little stream leading up from the ocean, only about 50 or 60 miles long. They have found that 20 to 22 ft. depth wouldn't do. They have 25 feet and they are before Congress at this session to get it increased to 30 feet and the Committee, of which I have the honor to be Chairman, has reported a bill to give them their 30 feet depth. There isn't anything any more important to the development and the progress of this nation than the use of oil and its various products. There isn't anything that is multiplying in its use from day to day, with anything like the rapidity of oil, and there is no place where it is being shipped as it is down in those gulf ports. And there is one of the things that you have to do. We haven't any money in this Bill for deepening these harbors. We are simply going to adopt the project and then trust to Providence that we can persuade Congress that it is necessary to let this oil come to us just as cheaply as it can, let the cost of gasoline go down five cents, if it is possible to do so take it out of the transportation costs. Isn't that a real problem to be weighed against the St. Lawrence route? Isn't it as important to us as developing a waterway in the foreign country? And that is only one of our pressing needs. Here is the Ohio River. Congress over 26 years ago adopted the project of improving the Ohio River by locks and dams. In 1910, after seven of the 54 locks and dams were completed, we provided that we should complete that improvement within 12 years. Twenty-six years have passed. We have improved 500 miles of it, about half, and the rest remains to be done.

The Ohio runs between coal mines and forests, rich fields waving with grain and all the products of the soil and, in its upper portion, through a beehive of manufacturing plants which have caused that section to be called "The Workshop of the World;" and cheap transportation can be had to carry all these products from Pittsburg, Cincinnati, St. Paul, St. Louis, New Orleans and intermediate points; and all of those great American cities which we love just as much as we do Montreal and Toronto, which are just as near our hearts; yet how are we going to get the money to complete this great transportation project if we spend hundreds of millions of dollars upon one foreign waterway, when it is hard to wring thirty millions of dollars out of an unwilling Congress for all the waterways of this great country of ours.

And then the Mississippi flows down dividing our whole empire of states, with great grain fields on both sides of it, furnishing to the vast territory tributary to it a far shorter route to the sea than the St. Lawrence route, and the southwest pass needs to be improved, and it will take millions to complete the work. Where are we to find the money if we spend all our income on the St. Lawrence? We never have provided that the nation should deepen the harbors on the Mississippi and they are all filled and silted and haven't the requisite depth. Don't we need the money to do that? Shouldn't we provide it? Don't we love all those cities down there just as much as we do Canada? And isn't it just as important to the life and the prosperity of this nation as a whole, that that great river be improved?

And so you could go over the various waterways of the United States, taking them one by one, pointing to their use in the national system of transportation. Why, as I think of this St. Lawrence route, I think of something that is in the mind of this nation because the President has recently brought it to the attention of Congress. I think of the fact that during the war, at an enormous expense, at the expense of billions we built up a great Merchant Marine only to find that the effort to operate it lost us a million dollars a day for the 365 days of the year. And finally we threw up our hands in despair and said that we couldn't stand the losses and that we had demonstrated that the Government couldn't operate ships, and the President came to Congress and said that we must sell these merchantships, these hundreds of thousands of tons that we had built at this enormous expense, let them pass into private hands, but under the American flag. But he said it was demonstrated with equal clearness that owing to our high cost of labor it was impossible for private parties even with efficiency, with energy, with capacity, with all that goes to make business successful, it would be impossible for them to operate those ships successfully in competition with the cheaper paid labor of Europe and with the experienced seamanship of those countries, and so he proposed that we should subsidize the American Merchant Marine, pay them 30 to 50 millions of dollars a year in order to enable them to operate upon the ocean, as Congress is going to do it, in my judgment.

If it is impossible for an American Merchant Marine to operate upon the free ocean, the Atlantic and the Pacific, with all the advantages they offer, how I ask you, when you can only bring up the St. Lawrence a boat with 4000 tons capacity, which is uneconomical even on the ocean itself where they require at least 7500 to 10,000 tons to be economical, how are you going to induce private enterprise to enter upon any such business venture as navigating ocean ships of that capacity on the St. Lawrence route? Deepen and widen the St. Lawrence, spend your hundreds of millions of dollars, starve your own waterways in the United States, do this for a third of the life of one generation, ten years, and when you have the waterway there ready, to the depth and of the draft that the Joint Commission recommends, what are you going to do with it when you can't operate ships upon the ocean of proper tonnage to be economical, when you can't operate them without a subsidy, how are you going to get any one to operate them upon the St. Lawrence route?

And are you going to come then and ask for a subsidy for this route for a thousand miles up to Montreal from the ocean and then on to Duluth? And do you think that the nation is in condition to grant the subsidy or that they will believe in the enterprise when they have examined it sufficiently to subsidize the boats that would navigate the channel? I am thoroughly convinced that this is a vision.

The Two-Stage Current Transformer

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This paper presents a brief discussion of the current transformer as used with measuring and controlling apparatus with special reference to the degree of accuracy which can be attained in the ratio and phase angle. A new type of current transformer is then described, in which it is possible to secure much higher accuracy with a given amount of iron and copper in the transformer. In this new device the transformation is effected in two stages, the first yielding in the usual way a secondary current which is approximately correct in magnitude and phase, and the second yielding an auxiliary corrective current which, when combined with the first secondary current, gives a resultant current which very closely approximates to the secondary current which would be furnished by an ideal current transformer having no errors. The two currents may easily be combined by having two like windings in the devices operated, one for the main and one for the auxiliary secondary current.

The mathematical theory of the two-stage current transformer is developed and applied. Experimental curves are given to compare the performance of the new transformer with that of an ordinary simple current transformer of good average performance. The effect of mutual inductance between the external secondary circuits is discussed, and some of the special advantages of the new transformer are given.

THE SIMPLE CURRENT TRANSFORMER

The term "current transformer" as ordinarily used refers to a transformer used to deliver to electrical measuring and controlling devices a definite fraction of the line current. It consists essentially of a core of magnetic material on which are wound two coils, one of which, usually of a few turns of large wire, is connected in series with the high-voltage circuit, while the other coil (usually of a greater number of turns of smaller wire) supplies a secondary induced current which operates the measuring and controlling devices in the secondary circuit. The impedance of the external secondary circuit is properly referred to as the secondary burden.

In order that a secondary current may be induced, a certain component of the primary current must be used to produce the necessary magnetization, and to supply the core loss. The core being of iron it is readily appreciated that this component of current varies with (1) secondary burden, (2) frequency, (3) magnitude of the secondary current. Because this component does not vary directly with the secondary current, the ratio of the two currents varies with any changes in the above three factors occurring either separately or jointly. Also, the electrical phase difference between the primary current and the secondary current, which would be exactly 180 deg. in an ideal transformer, departs from 180 deg. by a small angle, the "phase angle," which varies with each of the three causes mentioned as affecting the ratio of currents. For the accurate operation of electrical measuring apparatus, especially wattmeters and watt-hour meters, it is necessary that the ratio of primary current to secondary current should always be constant in a fixed ratio and that the departure from the 180 deg. phase relation should be negligible. This should be true for all ordinary conditions of secondary burden, primary current and frequency. Changes in ratio affect the readings of instruments at all power factors while phase angles cause errors which greatly increase as the power factor is lowered. For example, in using a polyphase watt-hour meter for measuring the energy delivered over a three-phase system, a variation of 1 per cent in the ratio causes an error of 1 per cent in the registration, irrespective of the power factor. When the system is at 86.6 per cent or 50 per cent power factor, a phase angle of 20 minutes will cause errors of 0.3 per cent and 1.0 per cent respectively in the registration of the meter. While such errors in ratio and phase are known to exist, their effect upon the accuracy of the instruments to which they are connected is not always appreciated. In the past and even at the present day, many central-station men consider a current transformer as of absolute ratio and zero phase angle.

Besides the conditions already spoken of as affecting the ratio and phase angle of the ordinary current transformer, there is the question as to the magnetization of the core brought about during moments of opening and closing of the primary circuit or accidental opening of the secondary under load.

Voltage ("potential") transformers are inherently capable of a very much better performance than current transformers, especially as regards phase angle. The induction watt-hour meter has also been brought to a high state of development, and its performance on inductive and non-inductive loads is readily controlled by the user through the three standard adjustments (light-load, full-load, phase). The current transformer has lagged in development behind the other two essential elements of metering equipment. The only way to improve it radically, with the methods of construction commonly employed, is to use iron of magnetic qualities much superior to anything now commercially available. It is the purpose of this paper to show how the transformation of current for metering purposes can be brought up to an accuracy at least as high as that of the other component functions, by means of a device which we have called a "two-stage" current transformer.

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The two-stage current transformer (shown diagrammatically as two distinct transformers in Fig. 1) inherently and automatically effects a correction of current ratio and phase angle between primary and secondary currents to a high degree of accuracy and within wide limits of secondary burden. This is effected in a manner which may be called a "multi-stage" transformation in which one transformer (the one at the left in Fig. 1) is used to effect the transformation in the ordinary way, yielding a current which is approximately correct as to magnitude and phase. The primary current and this secondary current are then passed through two windings of the second current transformer in which the ratio of secondary turns to primary turns is equal to the desired ratio of primary current to secondary current, the two currents being sent through their respective windings in such a way that their magnetizing effects upon the core (in ampere-turns) tend to oppose each other. (This exact ratio of turns is in contrast to the fact that in ordinary current transformers as now constructed, in order to secure approximately the desired ratio, one or more turns of the secondary winding must be omitted from the number which would be required by an ideal transformer). This second current transformer is provided with another winding called the auxiliary secondary, having very approximately the same number of turns as the principal secondary winding.

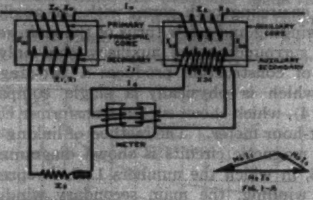

Fig. 1—Elementary Diagram of Electric and Magnetic Circuits of Two-Stage Current Transformer shown as Two Separate Transformers

It will be evident that if the first transformer is operating under conditions such that the secondary current happens to be exactly correct in magnitude and phase, the ampere-turns of the two windings of the second transformer will annul each other at every moment, and will produce no resultant magnetization in the core of the second transformer and as a result no current will flow in the auxiliary secondary winding.

If, however, as is usually the case in practise, the secondary current produced by the first transformer deviates from the desired ideal value in magnitude or phase angle, or in both, this current and the primary current flowing in opposite directions around the core of the second transformer produce a resultant magnetizing force which acts upon this core. If the auxiliary secondary be now connected to an external circuit, a current will flow which will tend to reduce the flux in the auxiliary core to zero. Under suitable conditions this auxiliary secondary current closely approximates in magnitude and phase to the current which must be vectorially added to the principal secondary current to produce a current such as would be given by an ideal transformer of exact ratio and zero phase angle.

The relations involved may be seen from the vector diagrams of Fig. 2, in which (a) is a simplified diagram of the action of an ordinary current transformer. $O\,F$ represents the direction of the flux in the core, $O\,E_1$ that of the induced secondary e. m. f.; their magnitudes are immaterial for the present discussion. With the usual case of a secondary circuit having resistance and inductance, the secondary current $O\,I_1$ will lag behind $O\,E_1$, and if the secondary coil has one turn, $O\,I_1$ may also represent the secondary ampere-turns. $O\,A$ is drawn of length equal to $O\,I_1$ and 180 deg. away from it, and represents the component of the primary ampere-turns which balances the secondary ampere-turns. To produce the flux and supply the core losses a magnetizing current I_m must flow through the one-turn primary, and I_m shows the magnitude and direction of this current and its magnetizing ampere-turns. Combining $O\,A$ and $O\,I_m$, we get the vector $O\,I_0$, which represents the primary current and its ampere-turns. It may be seen that since $O\,A$ is shorter than $O\,I_0$, I_1 is smaller than the desired value. (In practise, this is usually corrected, for any given set of conditions, by "dropping secondary turns"; that is, by making their number slightly less than the number required by an ideal transformer. However, for any other set of conditions, the current I_m will in general not change in such proportion to the other currents as to keep the ratio at the desired value.) Also, since $O\,A$ leads $O\,I_0$ by the angle α, the secondary current has a phase error ("phase angle") of this amount.

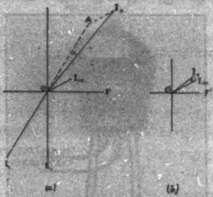

Fig. 2—Vector Relations of the Two-Stage Current Transformer

If we pass $O\,I_0$ and $O\,I_1$ through one-turn windings surrounding another core in such a way that their magnetizing effects are substantially in opposition, their resultant magnetizing force will be equal to $O\,I_m$. These two opposing windings may thus be regarded as equivalent to a one-turn primary winding traversed by the current I_m. Then in a third one-turn closed-circuit winding around this core (see Fig. 2 (b)) the current I_4 will be induced. It is evident that if this current be vectorially added to $O\,A$ of Fig. 2 (a) the resulting current will be very much closer to $O\,I_0$ in magnitude and phase than is $O\,A$.

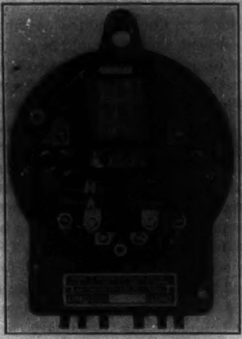

FIG. 3—MOTOR ELEMENT OF WATT-HOUR METER, SHOWING THE TWO CURRENT WINDINGS REQUIRED FOR USE WITH THE TWO-STAGE CURRENT TRANSFORMER

The current from the auxiliary secondary may be readily utilized by providing the meter (or other devices) with two identical current windings connected respectively to the main and auxiliary secondary circuits, as shown in Figs. 1 and 3. Under such conditions the total ampere-turns in the windings of each instrument so connected to the transformer system will be for all practical purposes exactly equal to the ampere-turns derived from an ideal transformer. The mathematical treatment of the electric and magnetic network involved is given in the appendix to this paper.

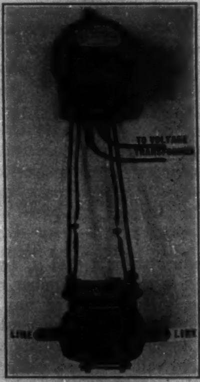

FIG. 4—TWO-STAGE CURRENT TRANSFORMER CONNECTED TO WATT-HOUR METER

Instead of the two physically distinct transformers shown diagrammatically in Fig. 1, it is more convenient to use a single primary winding and a single secondary winding encircling both cores, with the auxiliary secondary winding and a few turns of the main secondary winding surrounding the auxiliary core only.[1] This method of construction produces a two-stage transformer which is physically a single compact unit (see Fig. 4), which shows such a transformer connected to a watt-hour meter. The method of linking the electric and magnetic circuits is shown diagrammatically in Fig. 5, in which the numbers 1, 2, 3 represent the primary winding, the main secondary winding, and the auxiliary secondary winding respectively.

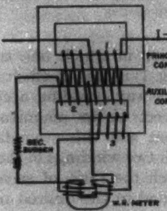

FIG. 5—ELECTRIC AND MAGNETIC CIRCUITS OF TWO-STAGE CURRENT TRANSFORMER MADE AS A STRUCTURAL UNIT

COMPARATIVE PERFORMANCE

Without going into details concerning the causes limiting the accuracy of current transformers having simple secondary windings, it is sufficient to recognize that a higher degree of accuracy in current transformers is desirable in order to bring up the accuracy of the readings of the meters and indication of the instruments which they operate. Let us consider the effect of such errors when the secondary is connected to a watt-hour meter which, for the purpose of this discussion, is assumed to be correct for all loads and power factors within the limits considered. If the meter were connected directly to the line the speed would be proportional to

$$S = E\,I\cos\theta$$

and if we assume next that a current transformer of nominal 1:1 ratio is interposed we would have the speed proportional to

$$S' = \frac{E\,I}{R}\cos(\theta - \alpha)$$

where R is the value, as taken from the calibration curve of the transformer, of the quotient, true ratio divided by marked ratio, and α is the small angle (the "phase angle") by which the reversed secondary current leads the primary current.

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[1] This construction was suggested by Dr. F. B. Silsbee.

When operating at unity power factor the term cos $(\theta - \alpha)$ is almost exactly equal to unity, so that the per cent registration of the meter will be almost inversely proportional to R.

As the power factor decreases the effect of α is felt more and more. Since for inductive loads the value of θ is positive there will be a tendency for the meter to run faster as the power factor is lowered. As the load is lowered the values of both R and α increase and in general there is a slight tendency for one to compensate the other, yet in most cases the meter will actually exhibit an increased per cent registration on inductive loads. For leading power factors the opposite is true and as the power factor is lowered the meter becomes slower and slower.

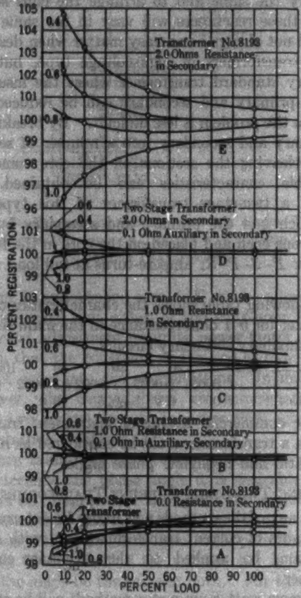

Fig. 6—Comparative Performance of Simple Current Transformer and Two-Stage Current Transformer

Fig. 6c shows this characteristic on inductive loads very clearly. The data as plotted show the degree to which the accuracy of a meter is affected when connected to a line through a modern simple current transformer. This transformer exhibits a good average performance. Transformers of considerably lower accuracy are in service and some of heavier modern designs show a higher accuracy. The curves show the per cent registration of the meter for various loads and at power factors as indicated. Without the transformer the per cent registration would in each case have been 100. The data were taken by direct measurement rather than by computation from ratio and phase-angle curves. In the case cited the secondary burden was 1 ohm resistance plus the resistance of the meter. This particular transformer had about 1200 ampere-turns at full load in the primary. A two-stage transformer was built having about the same amount of iron in its structure but using only one-half the number of ampere-turns. Data were taken on this transformer when connected to a meter and with various values of secondary burden. For zero secondary burden there was practically no deviation from 100 per cent registration for all loads and power factors. Figs. 6B and 6D show the results using secondary burdens of one ohm and two ohms respectively and in both cases there is practically no deviation from 100 per cent registration for all loads above 20 per cent. Figs. 6C and 6E show results which do not even compare favorably with A, B and D, although the secondary burden in case C was very favorable to high accuracy. Fig. 6A shows in full lines the performance of the ordinary current transformer when the secondary burden is only a meter element and 0.1 ohm lead resistance. The dotted line shows the performance of the two-stage transformer under the same conditions. For the latter the curves for the various power factors were so nearly coincident that they are shown as one line.

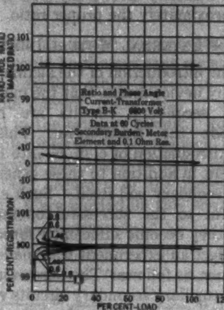

Fig. 7—Ratio, Phase-Angle and Performance Curves of Two-Stage Current Transformer

Fig. 7 shows the conventional ratio and phase-angle curves for the two-stage current transformer with a secondary burden consisting of a watt-hour meter and 0.1 ohm resistance. The lower set of curves, like those of Fig. 6, shows the performance as a function of both ratio and phase-angle.

The above data show the great utility of the two-stage transformer in obtaining the highest degree of accuracy in electric metering when the use of a current transformer becomes necessary. When used on switchboards the auxiliary secondary need be connected only to the wattmeters and watt-hour meters, since in general an error of 1 to 2 per cent in the indications of ammeters is of no serious consequence.

Watt-hour meters operated from two-stage current transformers need not be calibrated to compensate for inaccuracies in the transformers themselves, since the main secondary and the auxiliary secondary together provide an effective current which is at all times in the proper phase with and ratio to the primary current. This condition is practically independent of any change of secondary burden, frequency, or aging effects in the main core, and should the main secondary become open-circuited the auxiliary secondary will still provide current in approximately the proper ratio.

EFFECT OF EXTERNAL MUTUAL INDUCTANCE

In general the introduction of the auxiliary corrective current into any device means that the main secondary and auxiliary secondary circuits are magnetically coupled outside the transformer. This condition results in the introduction of e. m. fs. into the auxiliary secondary circuit in addition to those generated within the auxiliary secondary coil itself. Such e. m. fs. may become harmful to the successful operation of the transformer if they become sufficiently large. In order to show this effect an experiment was made on a two-stage transformer, as follows: The burden in both main secondary and auxiliary secondary circuits was approximately 0.25 ohm, and 0.79 mh. inductance. The constants of the transformer were first determined with the above secondary burdens and the test repeated using a mutual inductance of 0.21 mh, to couple magnetically the secondary and auxiliary secondary outside the transformer. The tests were made at 60 cycles.

The following table shows the change in constants for the condition with and without mutual inductance:

WITHOUT MUTUAL INDUCTANCE

Per Cent Load....	10	20	40	60	100
Ratio............	1.0017	1.0012	1.0010	1.0010	1.0010
Phase Angle......	5.5′	3.5′	1.5′	0.7′	−0.7′

WITH MUTUAL INDUCTANCE

Ratio............	1.016	1.014	1.011	1.010	1.007
Phase Angle......	5.2′	2.0′	0.0′	−3.5′	−5.6′

The above figures show that the introduction of mutual inductance between the main secondary and auxiliary secondary circuits outside the transformer is at least harmful to the ratio of the transformer. It should be noted, however, that the mutual inductance used in the above experiment was about four times as great as that between the two current windings of a watt-hour meter. Furthermore, it is a simple matter to provide an external corrective mutual inductance of equal numerical value but of opposite sign, thus canceling the mutual induction taking place in the meter. This device would be a small laminated core with two windings.

The usual practise of keeping the secondary burden as low as possible should be adhered to in the case of the auxiliary secondary, and the corrective current should be applied only to apparatus where it is required from the standpoint of accuracy.

SOME FEATURES OF DESIGN

From a practical standpoint it is desirable to make the mutual reactances between primary and auxiliary secondary and between main secondary and auxiliary secondary the same and to arrange the coils so that both of these reactances will vary in the same ratio. This will not always be an easy matter when designing current transformers of high-voltage type, but in a laboratory standard transformer where the insulation between primary and secondary can be reduced to a minimum the problem is less difficult. By breaking up the primary and secondary into a number of sections and interleaving the sections on the core some very remarkable characteristics can be obtained. For example, a two-stage transformer of this type was built which had the primary and secondary built in two sections each and placed on the core in the following order: *P- S- P- S*; ampere-turns at full load, about 900.

The following table shows the characteristics of this transformer for 0.1 ohm resistance in the main secondary and auxiliary secondary circuits.

Per Cent Load....	10	20	30	60	100
Ratio............	1.0005	1.0005	1.0002	1.0002	1.0001
Phase Angle......	2.0′	1.0′	0.5′	0.0′	0.0′

For the commercial testing of instrument transformers such a transformer could be considered as having a fixed ratio and negligible phase angle.

TESTING TWO-STAGE CURRENT TRANSFORMERS

Almost any of the methods now in use for determining the constants of current transformers can, with slight modification, be applied to the two-stage current transformer.

The Agnew watt-hour meter method[2] will be of particular interest to the laboratory of limited facilities, since it gives results which are sufficiently accurate for all commercial purposes and requires no instruments or apparatus of precision except a current transformer whose constants are known. When testing a transformer of one-to-one ratio even this special transformer is not necessary. The ratio and phase angle as determined by any one of these methods will be termed the "effective" ratio and phase angle since they are determined from the vector sum of two currents.

Fig. 8 shows the arrangement for testing a one-to-one ratio two-stage current transformer. Two watt-hour meters *a* and *b* are each equipped with two sets of series coils having the same number of turns as a standard five-ampere coil. Each disk is marked in hundredths of a revolution. The potential coils are connected in parallel to a source of e. m. f. of the same frequency as that which supplies current to the primary of the current transformer and arrangements should be made whereby the phase relations between the main current I_0 and applied e. m. f. E can be altered. It is not necessary that either of the watt-hour meters be in correct adjustment on unity power factor since it is shown that the constants of the two watt-hour meters do not enter into the computations. In many cases, however, the computations are somewhat lessened if the two meters are kept in rather close agreement as regards their constants.

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[2] Agnew, Watt-hour Meter Method of Testing Instrument Transformers, Scientific Paper of the Bureau of Standards No 233, 1914; Craighead and Weller, *General Electric Review* Vol. 24, p. 642, 1921.

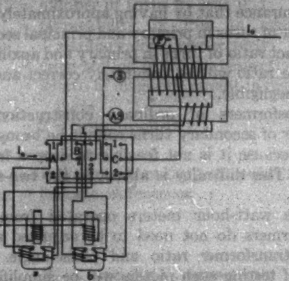

FIG. 8—DIAGRAM OF CONNECTIONS FOR AGNEW TWO-WATT-HOUR-METER METHOD OF TESTING A 1:1 RATIO TWO-STAGE CURRENT TRANSFORMER

When taking readings at low power factors in order to determine the phase angle it is desirable that the meters be in agreement as regards the angle by which the shunt-field flux lags behind the voltage. It is not necessary that the flux from each potential pole be exactly 90 deg. behind the voltage, but it is desirable that the angle be the same in both. For this reason it has been found desirable to adjust the meters to agreement at unity and at some low power factor; say 20 per cent.

Three double-pole double-throw switches are provided as shown. By throwing the switches first in the position $A_1\,B_1\,C_1$ meter *a* is in the primary of the transformer with one of the series coils disconnected while meter *b* has its windings connected to the secondary and auxiliary secondary respectively of the two-stage transformer. By throwing the switches into the position $A_2\,B_2\,C_2$ the relative position of the meters is interchanged.

If when the switches are in the position $A_1\,B_1\,C_1$ we designate by a_1 and b_2 the revolutions recorded on the meters *a* and *b* in a given time, and by a_2 and b_1 the revolutions recorded for the two meters *a* and *b* when the switches are in the position $A_2\,B_2\,C_2$, we have the ratio of the transformer

$$R = \sqrt{\frac{a_1\,b_1}{a_2\,b_2}} \qquad (1)$$

if the applied e. m. f. E is in phase with the current I_0.

If the applied e. m. f. is not in phase with the current the quantity under the radical may be termed R', the *apparent ratio* of the transformer, since it is dependent not only upon the effective ratio of the currents but upon the phase angle as well.

From the standpoint of computations it is desirable to make b_1 and b_2 the same, in which case, neglecting terms of second and higher orders, we have

$$R = \sqrt{a_1/a_2} = 1 + \frac{a_1 - a_2}{2\,a_2} \qquad (2)$$

When taken at power factors other than unity $1/R' \times 100$ would be the per cent registration which a meter would exhibit when placed in the secondary circuit of the current transformer if it were correct when placed in the primary circuit. Such data would be of particular interest to the practical meterman who desires to know the effect of both ratio and phase angle upon the accuracy of the meter. The curves shown in Fig. 6 are plotted on this basis.

Phase angles are determined by taking readings at both unity and low power factor for the same volt-ampere load, using a wattmeter, voltmeter and ammeter to determine the power factor as regards the primary current and applied voltage E. For this case we denote by a_1', a_2', b_1', b_2', the readings corresponding to a_1, a_2, b_1, b_2 in the test at unity power factor. Upon making $b_2' = b_1'$ we have the phase angle

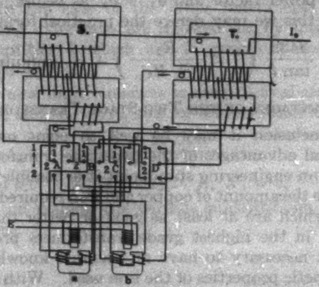

FIG. 9—DIAGRAM OF CONNECTIONS FOR AGNEW TWO-WATT-HOUR-METER METHOD OF TESTING TWO-STAGE CURRENT TRANSFORMERS OF RATIO OTHER THAN UNITY

$$\alpha = \tan^{-1}\left[\frac{1}{\tan\theta}\,(1 - R/R')\right] \qquad (3)$$

where $R' = \sqrt{a_1'/a_2'}$ is the apparent ratio at the low power factor and R is the ratio at unity power factor while θ is the angle between E and I_0.

This formula gives the phase angle in radians. For practical purposes, since the angle is small, we may take the angle as equal to the tangent. Doing this and multiplying by 3438 to reduce to minutes, we have

$$\alpha = \frac{3438}{\tan \theta} (1 - R/R') \text{ (minutes)} \qquad (4)$$

Fig. 9 shows the arrangement for testing a two-stage current transformer whose nominal ratio is different from unity. The transformer S is used as the standard and may be of either the two-stage or simple type. If of the simple type there will be no auxiliary secondary connections from this transformer to the switch as shown. If we let

R_1 = ratio of the standard transformer S
α_1 = phase angle of the standard transformer S
R_2 = ratio of the two-stage transformer B
α_2 = phase angle of the two-stage transformer B

then with the same meaning attached to the a and b symbols as before

$$R_2 = R_1 \sqrt{a_1/a_2} = R_1 \left(1 + \frac{a_1 - a_2}{2\, a_2}\right) \qquad (5)$$

$$\alpha_2 = \tan^{-1}\left[\frac{1}{\tan \theta}\left(1 - \frac{R_2}{R_1 R_2'}\right)\right] + \alpha_1 \qquad (6)$$

where $R_1 R_2' = R_1 \sqrt{a_1'/a_2'}$ is the apparent ratio at the low power factor and $b_1' = b_2'$ as before.

From this we may derive the practical formula

$$\alpha_2 = \frac{3438}{\tan \theta}\left(1 - \frac{R_2}{R_1 R_2'}\right) + \alpha_1 \text{ (minutes)} \qquad (7)$$

ADVANTAGES OF THE TWO-STAGE TRANSFORMER

In conclusion it may be well to point out some additional advantages of the two-stage transformer.

From an engineering standpoint it is possible greatly to reduce the amount of copper and iron required to give results which are at least as good or better than now attained in the highest grade transformers produced. It is not necessary to have an accurate knowledge of the magnetic properties of the iron used. With reasonable amounts of materials used the inaccuracy of metering due to the presence of current transformers can be reduced to a negligible quantity. This is in contrast to the average simple current transformer whose accuracy under service conditions often leaves much to be desired. Even with a given secondary burden it cannot be compensated for all loads and power factors, as the curves clearly show.

The results of a questionnaire sent out recently to the large electric power companies by the Meter Committee of the National Electric Light Association[3] showed that, "The installation of separate current transformers was reported in practically all cases for watt-hour meters, while indicating instruments and other devices, including relays, are combined on the same transformer." The use of one two-stage transformer would give as good or better metering accuracy, and would save the cost of the extra transformer and the space occupied by it.

Current transformers of very large range, beyond the maker's facilities for precision testing, can be made with the assurance that by having approximately the correct number of turns in primary and principal secondary and the exact ratio of turns in primary and auxiliary secondary the ratio will be accurately correct and the phase angle negligible.

Transformers of ordinary construction of small number of secondary turns cannot be brought to exact ratio because it is not feasible to drop a fraction of a turn. This difficulty is absent in the two-stage transformer.

Since watt-hour meters operated from two-stage transformers do not need to be adjusted specially to offset transformer ratio and phase-angle errors, the work of testing such meters will be simplified and the cost of testing reduced.

An important possible application of the two-stage transformer is in the measurement of the output of a-c. generators on acceptance tests. In the case of large machines it is customary to stipulate a large penalty for each per cent by which the efficiency falls below the contract figure, and conversely a large bonus for an efficiency superior to that specified. It is therefore highly desirable to use current transformers which have a constant ratio and do not require troublesome corrections for phase-angle errors. The auxiliary winding can be applied to indicating wattmeters as well as to watt-hour meters.

Particularly on high-voltage circuits where accurate metering is so desirable the simple current transformers of best design show very poor characteristics. This is due to the separation of primary and secondary windings necessitated by the insulation requirements. This is particularly true of the Nicholson air-insulated transformer and the bushing type having low ampere-turns and long mean path of flux in the iron. In these cases the two-stage transformer will make possible a step well in advance of present-day methods of metering high-voltage systems.

Appendix

In the following discussion the mathematical relations underlying the action of the two-stage current transformer are established, and a comparison is made with the corresponding relations for the simple current transformer. In this connection the authors wish to acknowledge valuable assistance rendered by Dr. F. B. Silsbee.

The following symbols will be used:

I_0, I_1 and I_4 = primary, main secondary, and auxiliary secondary currents respectively

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[3] Report of N. E. L. A. Meter Committee, June 1921, p. 9, 44th Convention.

$X_0, X_1 \ldots X_4$ reactances of the several coils as indicated by the subscript and on Fig. 1

Z_3 = impedance of main burden plus resistance of coils 1 and 3

Z_4 = impedance of auxiliary burden plus resistance of coil 4

X_{01}, X_{23}, etc. = mutual reactances between coils indicated by the subscripts

$N_0, N_1 \ldots N_4$ = number of turns in coils 0, 1 . . . 4

μ_1, μ_4 = permeability of iron in main and auxiliary cores respectively

a_1, a_4 = cross-section of iron in respective cores

l_1, l_4 = length of magnetic circuit in respective cores

ω = $2\,\pi$ times frequency

j = $\sqrt{-1}$

D_1, D_4 = leakage factors (approx. equal to 1)

δ_{01}, δ_{23}, . . etc. = leakage differences

c = $\dfrac{a_4\,\mu_4\,D_4\,l_1}{a_1\,\mu_1\,D_1\,l_4}$

z_3, z_4 = Z_3/X_1 and Z_4/X_1 respectively

η_{34}. . . .etc. = $\delta_{34}\,\mu_4$

ζ = Z_4/X_4

Throughout the development, the currents, impedances, and permeabilities will be regarded as plane vectors and the final ratio will be obtained as a complex number whose modulus is the true ratio and whose argument is the phase angle.

Applying Kirchoff's laws to the two secondary circuits shown in Fig. 1 we obtain

$$I_1\,[Z_3 + j\,(X_1 + X_3)\,] + I_4\,j\,X_{34} = -\,I_0\,j\,(X_{01} + X_{23}) \tag{8}$$

$$I_1\,j\,X_{34} + I_4\,(Z_4 + j\,X_4) = -\,I_0\,j\,X_{24} \tag{9}$$

Solving these two simultaneous equations gives

$$I_1 = -\,I_0\,\frac{j\,(X_{01} + X_{23})\,(Z_4 + j\,X_4) + X_{34}\,X_{24}}{(Z_4 + j\,X_4)\,[Z_3 + j\,(X_1 + X_3)\,] + X_{34}{}^2} \tag{10}$$

$$I_4 = -\,I_0\,\frac{j\,X_{24}\,[Z_3 + j\,(X_1 + X_3)\,] + X_{34}\,(X_{01} + X_{23})}{(Z_4 + j\,X_4)\,[Z_3 + j\,(X_1 + X_3)\,] + X_{34}{}^2} \tag{11}$$

Now each of the reactances (X_{mn}) may be split up into a number of factors so that

$$\left.\begin{aligned}
X_1 &= \omega\,\frac{4\,\pi}{10}\,\frac{a_1}{l_1}\,\mu_1\,N_1{}^2\,D_1\\
X_3 &= \omega\,\frac{4\,\pi}{10}\,\frac{a_4}{l_4}\,\mu_4\,N_3{}^2\,D_4\,(1-\delta_3)\\
X_4 &= \omega\,\frac{4\,\pi}{10}\,\frac{a_4}{l_4}\,\mu_4\,N_4{}^2\,D_4\\
X_{01} &= \omega\,\frac{4\,\pi}{10}\,\frac{a_1}{l_1}\,\mu_1\,N_0\,N_1\,D_1\,(1-\delta_{01})\\
X_{23} &= \omega\,\frac{4\,\pi}{10}\,\frac{a_4}{l_4}\,\mu_4\,N_2\,N_3\,D_4\,(1-\delta_{23})\\
X_{24} &= \omega\,\frac{4\,\pi}{10}\,\frac{a_4}{l_4}\,\mu_4\,N_2\,N_4\,D_4\,(1-\delta_{24})\\
X_{34} &= \omega\,\frac{4\,\pi}{10}\,\frac{a_4}{l_4}\,\mu_4\,N_3\,N_4\,D_4\,(1-\delta_{34})
\end{aligned}\right\} \tag{12}$$

In these expressions the leakage factors D_1 and D_4 are those by which the inductances of coils 1 and 4 respectively differ from those computed from the well-known simple formula for uniformly and closely wound ring coils. In the case of the other reactances the corresponding differences are allowed for by introducing the quantities δ which are in practical cases small compared with 1.

If we now limit ourselves to the practical case where $N_3 = N_4$ and $N_0 = N_1$, and for abbreviation let

$$c = \frac{a_4\,\mu_4\,D_4\,l_1}{a_1\,\mu_1\,D_1\,l_4} \tag{13}$$

and also let $\quad Z_3/X_1 = z_3, \quad Z_4/X_1 = z_4 \quad$ (14)

we get, on making the various substitutions, the two equations:

$I_1 = -\,I_0 \times$

$$\frac{\dfrac{N_2}{N_1}\left\{1-\delta_{01}+\dfrac{N_3}{N_1}\,c\,(-\,\delta_{23}+\delta_{31}+\delta_{24}-\delta_{34}\,\delta_{24})-j\left[z_4\left(\dfrac{N_1{}^2}{N_3{}^2\,c}+\dfrac{N_1}{N_3}\right)-z_4\left(\dfrac{\delta_{01}\,N_1{}^2}{N_3{}^2\,c}-\dfrac{\delta_{23}\,N_1}{N_3}\right)\right]\right\}}{1-\dfrac{N_3{}^2}{N_1{}^2}\,c\,(-\,\delta_3+2\,\delta_{34}-\delta_{34}{}^2)-j\left[\,z_3+z_4\left(1-\delta_3+\dfrac{N_1{}^2}{N_3{}^2\,c}\right)\right]} \tag{15}$$

and

$I_4 = -\,I_0 \times$

$$\frac{\dfrac{N_2}{N_1}\left[\dfrac{N_1-N_3}{N_3}-\dfrac{N_1}{N_3}\,\delta_{24}+\delta_{01}+\delta_{34}+\dfrac{N_3}{N_1}\,c\,(-\delta_3-\delta_{24}+\delta_{23}+\delta_{34}-\delta_{23}\delta_{34}+\delta_3\delta_{24})-jz_3\,\dfrac{N_1}{N_3}\,(1-\delta_{24})\right]}{1-\dfrac{N_3{}^2}{N_1{}^2}c\,(-\,\delta_3+2\delta_{34}-\delta_{34}{}^2)-j[z_3+z_4(1-\delta_3+\dfrac{N_1{}^2}{N_3{}^2\,c})]} \tag{16}$$

While these separately are very complicated functions of the leakage factors and burdens it will be noted that the δ's and z's are in practise small compared to 1 and hence we may neglect the higher powers and products of these quantities entirely. If this is done the division of numerator by denominator may be carried out explicitly and we obtain

$$I_1 = -I_0 \frac{N_2}{N_1} \Big[1 - \delta_{01} + \frac{N_3}{N_1} c \, (-\delta_{23} + \delta_{34} + \delta_{21}) - \frac{N_3^2}{N_1^2} c \, (2 \, \delta_{34} - \delta_3) + \ldots + j \left(z_3 + z_4 \frac{N_3 - N_1}{N_3} + \ldots \right) \Big] \qquad (17)$$

$$I_4 = -I_0 \frac{N_2}{N_1} \left\{ \frac{N_1 - N_3}{N_3} + \delta_{01} - \frac{N_1}{N_3} \delta_{24} + \delta_{34} + \frac{N_3}{N_1} c \, (\delta_{23} - \delta_{34} - \delta_{24}) + \frac{N_3^2}{N_1^2} c \, (2 \, \delta_{34} - \delta_3) + \ldots - j \left[z_3 - z_4 \left(1 + \frac{N_1^2}{N_3^2 c} \right) \right] \right\} \qquad (18)$$

It will be seen that most of the terms (e. g., δ_{01}) of (**18**) are equal in magnitude and opposite in sign to the corresponding terms in (**17**), which is of course the mathematical expression for the physical fact that I_4 has very nearly the correct value to compensate for the departure of I_1 from its ideal value of $-I_0 \, N_2/N_1$.

If therefore we compute the effective ratio in the usual form we get, after a rearrangement of terms

$$\text{Ratio} = \frac{I_0}{I_1 + I_4} = -\frac{N_3}{N_2} \left\{ 1 - \frac{N_3}{N_1} \delta_{34} + \delta_{24} + \ldots + j \left[z_4 \frac{(N_1 - N_3) N_1}{c N_3^2} + \ldots \right] \right\} \qquad (19)$$

The corresponding expression for a single-stage transformer of the usual type is

$$\text{Ratio} = \frac{I_0}{I_1} = -\frac{N_1}{N_0} [1 + \delta_{01} + \ldots - j \, (z_3 + \ldots)] \qquad (20)$$

A comparison of equations (**19**) and (**20**) shows at once the advantages of two-stage transformation. If N_1 is made equal to N_3 then the ratio in (**19**) becomes independent of the secondary burdens, and if in addition $\delta_{34} = \delta_{24}$ (*i. e.* if coils 3 and 2 have equal mutual inductances on coil 4) then the ratio becomes constant and equal to N_3/N_2.

To see in more detail the effect of various conditions on the operation of the apparatus we may make some further algebraic transformations and must introduce some physical assumptions. It is evident from (**20**) that if δ_{01} and z_3 were constants, ordinary current transformers would have a constant ratio and phase angle at any given frequency and burden. Consequently the entire variation of transformer ratio with current and the main part of its variation with frequency and burden are due to the fact that the permeability is not constant and the core loss does not vary in proportion to the square of the flux density. In the group of equations (**12**) no explicit mention was made of core loss but this may readily be taken care of by considering μ to be a complex quantity having a real component proportional to that component of the induced voltage in quadrature with the magnetizing current and an imaginary component proportional to the core-loss component of the induced voltage. The leakage differences δ are roughly a measure of the ratio of the air leakage flux peculiar to one coil to the total flux which is mainly in the iron. Consequently these quantities, roughly at least, will be inversely proportional to the permeability of the iron. Also the quantities z_3 and z_4 involving, as they do, X_1 or X_4 in the denominator will be inversely proportional to μ. We may therefore at least approximately set

$$\left.\begin{aligned} \delta_{34} &= \eta_{34}/\mu_4 \\ \delta_{24} &= \eta_{24}/\mu_4 \\ z_3 &= \zeta_3/\mu_4 \\ \frac{N_1^2 z_4}{N_3^2 c} &= \frac{\zeta_4}{\mu_4}, \quad \text{or} \quad \zeta_4 = \frac{Z_4}{X_4} \mu_4 \end{aligned}\right\} \qquad (21)$$

Inserting these relations in (**13**) and (**14**) gives

Ratio (two-stage) =

$$-\frac{N_3}{N_2} \left[1 + \left(\eta_{24} - \frac{N_3}{N_1} \eta_{34} + j \, \zeta_4 \frac{N_1 - N_3}{N_1} \right) \frac{1}{\mu_4} \right] \qquad (22)$$

and

$$\text{Ratio (single-stage)} = -\frac{N_1}{N_0} [1 + (\eta_{01} - j \, \zeta_3) \frac{1}{\mu_1}] \qquad (23)$$

The equations cannot be profitably pushed farther than this unless the permeability can be expressed as a definite function of the flux density. It may be noted, however, that the flux density at which a core works is proportional to the net induced voltage per turn and varies inversely as the frequency. Consequently for high frequencies or small currents and burdens μ_1 will be small but fairly constant while with higher flux densities corresponding to lower frequency or larger current and burden μ will be larger but will vary more rapidly with current. Since the auxiliary core has to circulate only the very small auxiliary current through the very moderate auxiliary burden, the flux density in it is low and μ_4 in equation (**22**) is fairly constant, though small. In the single-stage transformer, however, the flux must be sufficient to circulate the entire secondary current and μ_1 in equation (**23**) will vary rather rapidly with current.

The principal gain from two-stage transformation, however, is seen by the coefficient of $1/\mu_4$ in equation

(**22**), which involves only the *difference* of two nearly equal leakage factors instead of a single factor. Moreover, the main secondary burden does not enter at all into the first order terms in equation (**22**) for the two-stage transformer, and the auxiliary burden is multiplied by the factor

$$\frac{N_1 - N_3}{N_1}$$

which is always small and may be made zero if desired. To make $N_1 = N_3$ however in general will make I_4 larger than if N_1 is slightly less than N_3. The consequent increase in auxiliary flux density and in the variability of μ_4 and in second order terms may more than neutralize the improvement in the ζ_4 term.

Equation (**22**) shows very clearly the effect of external mutual inductance between the main and auxiliary secondary circuits, since such an effect is equivalent to increasing η_{34} and will directly destroy the balance between δ_{24} and δ_{34}. This effect is referred to at some length in the present paper.

On the whole it is seen that the errors of the single-stage transformer have been reduced to one order of magnitude smaller by the use of the two-stage transformation. This is confirmed by the experimental results which show that a transformer which operating single-stage has errors of several per cent will on two-stage operation show errors of only a tenth of this amount, or less.

Discussion

James R. Craighead: There are in addition to those outlined in this paper, several other methods of making phase angle correction in current transformers. The simplest is the use of a non-inductive shunt placed across the primary winding or across the secondary winding, which subtracts a certain amount of current either from the primary or the secondary side of the transformer. This current is in a phase position which is such that it tends to restore the remainder of the secondary current to the phase position of the primary current, and by so doing can diminish to some extent the usual leading (or positive) phase angle of the current transformer. Inductive reactance may be substituted for the non-inductive shunt where the phase angle is negative.

An extension of this method is the use of a separate winding on the core of the current transformer, which gives an opportunity of using other voltages than the voltage generated at the secondary terminals. This allows the use of condensance, reactance and resistance; and by using these three the sub-division of the current can be made so that the net current going through the meter for any given point can be brought more exactly into phase apposition. Both these methods produce a correct phase angle under only one condition, and change in current, frequency or secondary burden is usually accompanied by change in phase angle.

Consequently, this form also does not give a continuous or complete correction.

A third method requires the use of two current transformers. A main current transformer has the standard connection, with its primary in the primary line, and its secondary connected to the meter or other burden. An auxiliary current transformer is placed with its primary either in the primary line or the secondary line, and it has a ratio very different from the ratio of the first transformer.

This second transformer produces a very small current, roughly sufficient to produce a corrective result if applied either across the primary terminals of the main current transformer, or across the terminals of the burden. A combination can be made to produce a result which is somewhat better than a simple point correction, by selecting main and auxiliary transformer so that their characteristics tend to offset errors through same range. As the auxiliary transformer has a comparatively large number of turns, more accurate correction of ratio may be made than with a transformer of standard type. Full correction can be obtained under only one condition, as in the preceding method.

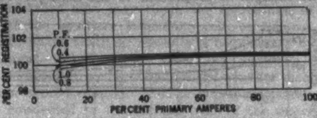

FIG. 1—CURRENT TRANSFORMER FOR METERING SERVICE—ACCURACY AT 60 CYCLES

Burden of 1.8 ohms resistance (45 voltamperes)

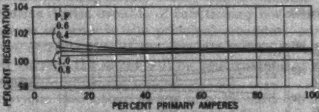

FIG. 2—CURRENT TRANSFORMER FOR METERING SERVICE—ACCURACY AT 60 CYCLES

Burden of one watthour meter and leads (0.15 ohm resistance, 3.75 voltamperes)

The method proposed by Mr. Brooks, while resembling the previous method in the use of two transformers, is distinctly different in principle. If the auxiliary secondary, which I prefer to call the tertiary is disconnected, the transformer consists of a core subdivided into two parts, with a common primary and secondary on both parts, the secondary being connected to an external burden. If then we connect the tertiary to a burden of low impedance, the corrective current drawn reduces the flux in the auxiliary core. This increases the impedance of the secondary circuit and increases the voltage developed in the secondary by the main core, and consequently the flux in the main core and its exciting current. The error in the total secondary circuit is therefore increased, and we get a subdivision into two circuits, one whose accuracy has been largely increased

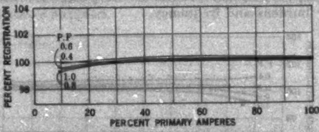

FIG. 3—CURRENT TRANSFORMER FOR METERING SERVICE—ACCURACY AT 60 CYCLES

Burden of 0.97 ohm resistance, 4.03 milli henries inductance (45 voltamperes at 0.54 power factor at 5 amperes 60 cycles) by the redistribution of the flux, and the other whose accuracy has been decreased by the same cause. The auxiliary core is really excited by the difference between the primary and secondary currents as a true primary current, and the tertiary winding tends to deliver a proportionate current. Since this difference is the error in transformation of the main transformer, the corrective current changes in proportion to the need for correction. Consequently moderate changes in frequency, secondary burden or primary current make only very small changes in accuracy. From this the Brooks plan is evidently applicable where it s desirable to obtain high accuracy over a very small portion of the secondary burden, as a watthour meter. Where the purpose is to obtain better general accuracy on a large burden, such as curve drawing instruments, balanced relays, etc., the method is not applicable.

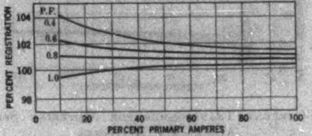

FIG. 4—CURRENT TRANSFORMER FOR METERING SERVICE—ACCURACY AT 25 CYCLES

Burden of 1.8 ohms resistance (45 voltamperes)

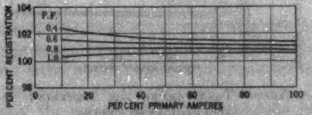

FIG. 5—CURRENT TRANSFORMER FOR METERING SERVICE—ACCURACY AT 25 CYCLES

Burden of one watthour meter and leads (0.15 ohm resistance 3.75 voltamperes)

Mr. Brooks has furnished curves showing the performance of an ordinary commercial type of transformer for comparison with his device. These results are not as good as may be obtained with the better grade of commercial transformers.

Figs. 1 to 6 show the accuracy of a meter (neglecting its internal error) operated from a current transformer of good standard type at power factors from unity to 0.4 lagging, with various secondary burdens and frequency.

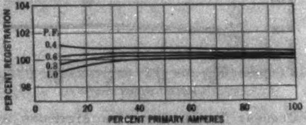

FIG. 6—CURRENT TRANSFORMER FOR METERING SERVICE—ACCURACY AT 25 CYCLES

Burden of 0.97 ohms resistance, 4.03 milli henries inductance, (45 voltamperes at 0.54 power factor at 5 amperes 60 cycles)

The first three show operation at 60 cycles, with burdens of (Fig. 1) 1.8 ohms non-inductive resistance, or 45 volt-amperes, at 5 amperes and 60 cycles; (Fig. 2) 0.15 ohms resistance or 3.75 volt-amperes (practically a watthour meter with its leads); and (Fig. 3) 0.97 ohms resistance with 4.03 milli-henries inductance or about 45 volt-amperes at 0.45 power factor. This last is the highest burden recommended for use with the transformer when a watthour-meter is included. The results show errors due to the transformer of less than 1 per cent, as compared with much larger errors shown by the transformer used as a comparison by the authors of the paper.

The next three figures show similar data for the same transformer and burdens at 25 cycles. In Fig. 4 is shown the effect of a non-inductive burden of 1.8 ohms—which is rare in metering practise—on the accuracy for comparison with Fig. 1. Fig. 5 shows the accuracy with burden of watthour meter and leads corresponding to Fig. 2, and Fig. 6 the accuracy with the full-rated burden for this service, corresponding to Fig. 3.

With the last condition, the maximum error is again reduced to close to one per cent, while the more severe condition shown in Fig. 4 causes a maximum error of over 4 per cent, approaching the amount shown in Mr. Brooks' example at 60 cycles. This, however, is a burden greater than is recommended for watthour meters to work with the transformer.

A study of the 25-cycle results shows that the average error through the ranges selected is in each case in the same direction. It may therefore be partly offset by adjustment of the potential transformer burden or of the watthour meter itself.

Perry A. Borden: In developing the two-stage current transformer, Mr. Brooks has eliminated what has been probably the worst feature in a-c. metering. Heretofore, about the only comfort we had lay in the possibility of the current transformer errors being to some degree compensated for by those of the voltage transformers. But this, even if true for one condition of the load could not be universally so.

While the two-stage principle, as applied to transformers of an inherently compact design and of high ampere-turns means a close approach to perfection, it would seem that its greatest application would lie in the field of air-insulated transformers for high-voltage work, and for bushing type transformers where the primary is, of necessity, limited to a single turn.

A limiting factor in the use of the two-stage transformer would appear to be introduced by the necessity of duplicating the secondary wiring both internally and externally to the meter. On large systems, where each installation is subject to the supervision of a trained meter-man, this would mean little difficulty; but on small utilities where the metering installations are made by a wireman with no court of appeal but the manufacturer's blueprint, the probability of error in the meter wiring would be double what it is now; and I think those who have had experience with meters installed by non-technical help, will agree that this is no small factor.

I should like to ask Mr. Brooks if he has made any studies or carried on experiments in the use of this transformer without the refinement of the extra winding in the meter. It would seem that the commendable features of the principle would be sacrificed but little by paralleling the secondary and the auxiliary windings in the meter, or even at the terminals of the transformer. If this could be done, the only objection to the device,—that of duplicate current circuits—would be at once removed.

F. C. Holtz: In reply to Mr. Craighead's remarks we might add that it was not our intention to show in this paper the characteristics of the best transformers to be had. We did, however, choose a transformer of good average characteristics—a type which represents a fair average of those in service today.

I should also like to inquire of Mr. Craighead the weight of the transformer whose characteristics were shown on the screen.

J. R. Craighead: It varies from 20 pounds up to about 1500. It is an average curve of the total amount of transformer.

F. C. Holtz: The two-stage current transformer can be made extremely light in weight. For example, we have made transformers of 200 amperes capacity with one turn, weighing approximately 13 pounds. This being the total weight of a transformer for 13,200-volt circuits.

The two-stage principle becomes particularly applicable for high voltages where it is necessary to obtain great separation between primary and secondary, and where the simple transformer cannot maintain the high standards of metering accuracy.

In reply to Mr. Borden's discussion, I should like to bring in an endorsement of his suggestion that an important application is that of the one-turn-primary current transformer. Where metering is done close to the generator bus, it is often found that the multiple turn transformer cannot withstand the effect of short circuits and a compromise is reached between the operating and meter departments through the installation of single-turn-primary current transformers. While such transformers do readily withstand the effects of short circuits, they very often fail to give satisfactory results in metering. This is particularly true of transformers of 200 amperes capacity and lower. Such transformers often show over 5 per cent variation in ratio from 10 per cent load to 100 per cent and have phase angles as high as 6. degrees on light loads. It is possible through the application of the two stage principle to build current transformers of the one turn primary type, which in addition to possessing the feature of indestructibility, have good electrical characteristics at low secondary burdens, such as for example, a meter element and .1 ohm resistance. Transformers of this type have been constructed which maintain correct ratio to within .3 per cent from 10 per cent to 100 per cent load, and whose phase angle is less than 10 minutes over the same range of load.

H. B. Brooks: Referring to Mr. Craighead's statement that the two-stage transformer is applicable only where it is desirable to obtain high accuracy over a very small portion of the secondary burden, we consider that it is only a question of design to obtain high accuracy over a large burden. In general, it is not necessary to do this, except in the case of watthour meters, for errors of even several per cent are not serious where the object is to obtain data as a guide in operating the plant. Of course, if the large burden introduces a relatively large mutual inductance between the main and auxiliary secondary circuits, corrective measures may have to be employed. The simplest is the use of an external mutual inductance of equal magnitude and opposite sign, by which the error in question may be reduced to zero.

Tests by Mr. Holtz show that in two-stage transformers having at least 800 ampere-turns the effective ratio and phase angle are not impaired by the introduction into the auxiliary secondary of burdens approximately equal to that of a graphic wattmeter and only to a slight extent by introducing a graphic ammeter or relay. He has made tests of an 800-ampere-turn two-stage current transformer and has found that a considerable burden can be introduced into the auxiliary secondary circuit without greatly affecting either ratio or phase angle, and that even at 25 cycles the results are quite satisfactory and superior to those obtainable in ordinary current transformers of the highest performance commercially obtainable.

While the use of duplicate current circuits is a drawback as Mr. Borden suggests, it is not nearly so serious as might at first appear. If the principal secondary circuit of a two-stage current transformer be opened under load, the auxiliary secondary winding will supply a current nearly equal to the desired total secondary current. This fact gives a means by which even an unskilled man may check the correctness of the connections of the auxiliary secondary coil, as follows. Assume that a three-phase watthour meter is to be operated by two two-stage current transformers. First the auxiliary secondary coils are disregarded, and it is immaterial whether their terminals are open or short-circuited. The principal secondary terminals are then connected to the current coils of the meter, and the correctness of the connections checked by diagram and polarity marks, or any other suitable method, just as if the current transformers were of the ordinary type. This done, the voltage is removed from one element, and the direction and approximate speed of rotation of the disk are noted. The auxiliary secondary terminals of the current transformer which is driving the meter are then connected to the meter terminals, and as a check, the principal secondary circuit is opened. If the auxiliary coil has been properly connected, the meter disk will continue to rotate in the same direction and at practically the same speed as before. If the auxiliary coil was connected backwards, the disk will run about the same speed as before, but in the opposite direction.

The fact above cited simply means that the auxiliary winding is a corrective device capable of functioning not merely over a limited range of error in the principal secondary current, but even in the extreme case of the absolute failure of the principal secondary current the meter will be kept running at nearly the correct speed.

It is obvious that other means may be used for facilitating correct connections, such as a cable of secondary wires of different colors, with corresponding markings on the meter terminals. In any case, the method of checking just outlined is simple and easily applied.

Answering Mr. Borden's question about the elimination of the extra winding in the meter, we would say that a considerable amount of work was spent on this point. By proper precautions, very accurate results may be obtained, but it is necessary for the best results to use a rather large burden in the principal (non-precision) secondary circuit, and furthermore, to have means for checking the accuracy. With the use of duplicate windings on the meter, low burdens may be used in the principal secondary circuit if desired, and if the transformer has been properly made and checked at the factory, no means of checking the accuracy are required, save only to see that the connections are properly made as above outlined.

Three Thousand Tests on the Dielectric Strength of Oil

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***Review of the Subject.**—Three thousand successive disruptive strength tests are herewith shown. These were made in six groups with 500 tests in each group under constant conditions of test. Three groups of tests were taken of standard insulating oil with three different shapes of the electrostatic field; small sphere gap, large sphere gap, and sphere-needle gap. One group of tests was made with commercial and another with chemically pure benzol. The last group was made with air as a dielectric. A brief review of results and conclusions follows.*

In measuring the voltage by a single sphere gap, set in air with reasonable care, the maximum error of test does not exceed 4 per cent and the average error is 1 per cent. In the average of six successive tests the maximum error decreases from 4 per cent to 2.9 per cent and the average error decreases from 1 per cent to 0.6 of 1 per cent.

In contrast to air, the behavior of oil is very erratic. Successive observations of its disruptive voltage, made under most carefully controlled conditions, differed by a percentage many times greater than the accuracy of the test,—the minimum value was as low as 49 per cent of the maximum. This inconstancy of the disruptive strength of oil appears inherent to the material. Little of the variation is dependent on the shape and size of the electrostatic field. Much of the variation is due probably to the complex chemical and physical nature of the oil.

Benzol gives far more consistent values of disruptive strength than oil, the more so the purer it is, but nevertheless benzol is much more erratic than air.

Under successive tests oil, first slowly and then more rapidly, deteriorates by carbonization due to the disruption. Benzol deteriorates very rapidly at first, and then becomes fairly constant. Filtration restores the initial disruptive strength, but the filtered material seems to deteriorate more rapidly than new material. This information indicates that there is either an intermediate chemical state of the disintegrated product or an absorption.

THE difficulty of obtaining consistent data on the behavior of insulating oil under disruptive dielectric stress is well known. It has been found that, because of this erratic behavior of oil, most available data on liquid insulation are so incomplete as to be of limited value.

To study this phenomenon of the erratic behavior of oil and its possible cause and explanation, 1500 successive breakdown tests were made on oil, 500 on one sample each (I) with a short sphere gap, which were described in a recent paper by the same authors,[1] (II) with a long sphere gap and larger spheres at higher voltage, (III) with a point-sphere gap, to see what effect the size or shape of the electrostatic field had.

Then 1000 successive tests were made with benzol, (IV) 500 with commercial benzol and (V) 500 with chemically pure benzol, to see whether the erratic behavior was specific to oil or shared by other liquid insulators.

Finally 500 successive tests were made in air at atmospheric pressure, to determine the possible accuracy of disruptive tests.

As Peek, Ryan and Whitehead have shown that the dielectric strength of air is uniform within errors of observation, comparison of this set of tests with the other five should show how much of their non-uniformity is due to the methods of testing, errors of observation etc.

Each sample was tested successively 500 times at the same gap length by gradually applying voltage to the electrodes (submerged in the sample) until the gap between them was broken down. All possible precautions were taken to prevent the presence of foreign particles, dust, etc. in the samples of liquid insulation, and to insure that each test was made in exactly the same manner. The rate of applying the voltage, which is all important in testing insulation, was made exactly the same for each test by using a motor operated rheostat. All 3000 breakdowns were taken in exactly the same manner as the first 500. Further details as to preparation of the sample, method of testing, development of curves, etc. will be found in the former paper. (loc cit.)

The data taken on each sample is shown graphically in two ways: (1) (*a*) The actual breakdown voltage in succession, (*b*) the average breakdown voltage, and (*c*) the per cent variation from the mean are plotted as ordinates against the number of the breakdowns as abscissas. (2) The per cent of the total number of breakdowns is plotted as ordinate against the per cent variation from the mean as abscissa. Each graph of this second group is a probability curve and was calculated from the data by the $\Sigma \Delta$ method[2]. The condition of the six groups of tests follow:

I. Five hundred breakdowns in oil between two one-cm. diameter spheres two mm. apart.

II. Five hundred breakdowns in oil between two 2.54-cm. diameter spheres 27 mm. apart.

III. Five hundred breakdowns in oil between a needle and 2.54-cm. diameter spheres 2 mm. apart.

IV. Five hundred breakdowns in commercial benzol between two one-cm. diameter spheres 2 mm. apart.

V. Five hundred breakdowns in pure benzol between two one-cm. diameter spheres 2-mm. apart.

VI. Five hundred breakdowns in air between two 2.54-cm. diameter spheres one cm. apart.

Figs. 1 to 3 show that the disruptive strength of oil is not constant and uniform, but varies in successive tests under identically the same conditions, over a wide range and in an entirely erratic manner. Comparison with Fig. 6, the air curve, shows that the variations

Presented at the Annual Convention of the A. I. E. E., Niagara Falls, Ont, June 26-30, 1922.

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[1] *Five Hundred Tests on the Dielectric Breakdown of Oil*, Hayden and Eddy, JOURNAL, A. I. E. E., February, 1922.

[2] Engineering Mathematics. C. P. Steinmetz.

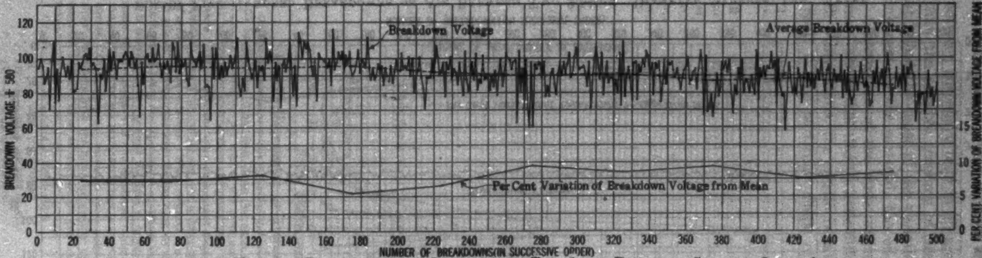

FIG. 1—FIVE HUNDRED BREAKDOWNS ON OIL BETWEEN TWO 1-CM. DIAMETER SPHERES 2 MM. APART

The points on the zigzag curve show the low-tension voltage (transformer ratio 580:1) at each of 500 successive breakdown tests made under constant conditions. Each of the ten points on the dotted line is the mean of the adjacent 50 breakdowns (25 on each side). Each of the ten points on the lower solid line shows the average variation of the adjacent 50 breakdowns (25 on each side) from their mean.

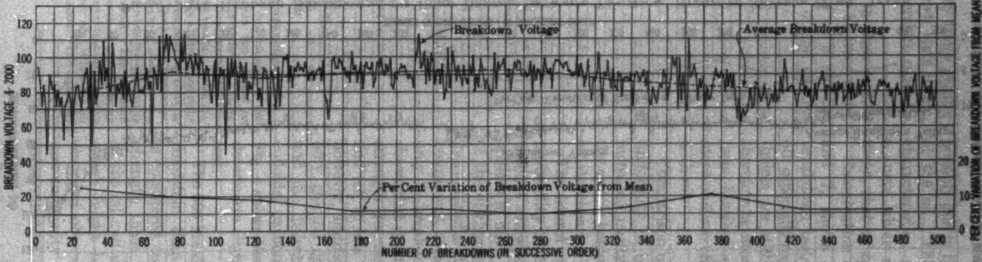

FIG. 2—FIVE HUNDRED BREAKDOWNS ON OIL BETWEEN TWO 2.54-CM. DIAMETER SPHERES 27 MM. APART

The points on the zigzag curve show the low-tension voltage (voltmeter coil ratio 2000:1) at each of 500 successive breakdown tests made under constant conditions.

Each of the ten points on the dotted line is the mean of the adjacent 50 breakdowns (25 on each side).

Each of the ten points on the lower solid line shows the average variation of the adjacent 50 breakdowns (25 on each side) from their mean.

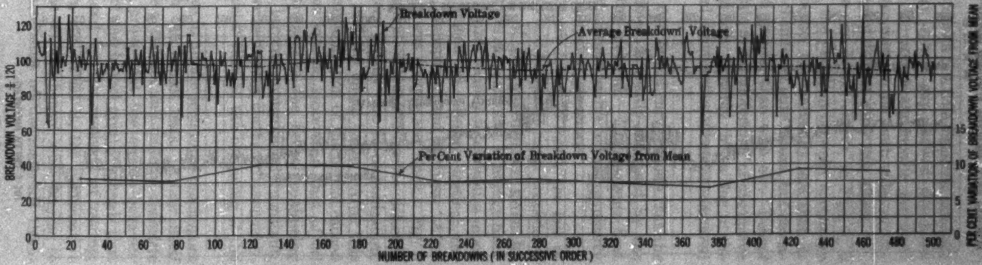

FIG. 3—FIVE HUNDRED BREAKDOWNS ON OIL BETWEEN 2.5-CM. DIAMETER SPHERE AND NEEDLE 2 MM. APART

The points on the zigzag curve show the low-tension voltage (transformer ratio 120:1) at each of 500 successive breakdown tests made under constant conditions.

Each of the ten points on the dotted line is the mean of the adjacent 50 breakdowns (25 on each side).

Each of the ten points on the lower solid line shows the average variation of the adjacent 50 breakdowns (25 on each side) from their mean.

The points on the zigzag curve show the low-tension voltage (transformer ratio 340:1) at each of 500 successive breakdown tests made under constant conditions.

Each of the ten points on the dotted line is the mean of the adjacent 50 breakdowns (25 on each side).

Each of the ten points on the lower solid line shows the average variation of the adjacent 50 breakdowns (25 on each side) from their mean.

After 300 breakdowns the benzol was removed from the container, refiltered, returned to the container and the tests continued.

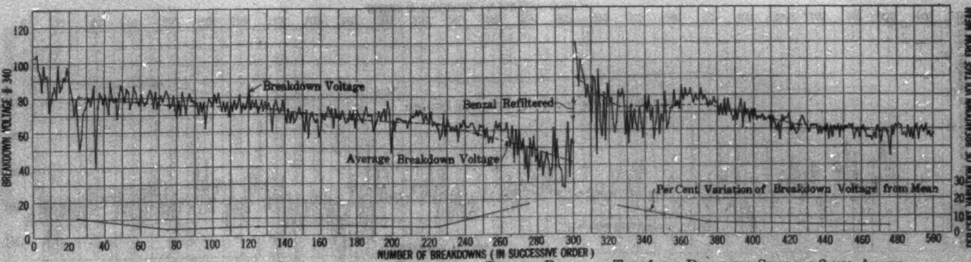

FIG. 4—FIVE HUNDRED BREAKDOWNS ON COMMERCIAL BENZOL BETWEEN TWO 1-CM. DIAMETER SPHERES 2 MM. APART

The points on the zigzag curve show the low-tension voltage (transformer ratio 340:1) at each of 500 successive breakdown tests made under constant conditions.

Of the 14 points on the dotted curve, each of the first 5 (at the left) is the mean of the adjacent 10 breakdowns (5 on each side). Each of the remaining 9 points is the mean of the adjacent 50 breakdowns (25 on each side).

The 14 points on the lower solid curve are distributed similarly. Each of the first 5 is the average variation of the adjacent breakdowns (5 on each side) and each of the remaining 9 is the average variation of the adjacent 50 (25 on each side) from their mean.

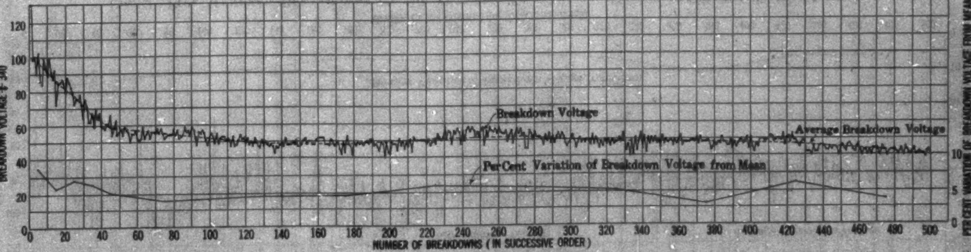

FIG. 5—FIVE HUNDRED BREAKDOWNS ON PURE BENZOL BETWEEN TWO 1-CM. DIAMETER SPHERES 27 MM. APART

The points on the zigzag curve show the low-tension voltage (transformer ratio 300:1) at each of 500 successive breakdown tests made under constant conditions.

Each of the ten points on the lower solid curve is the average variation of the adjacent 50-breakdown voltages (25 on each side) from their mean.

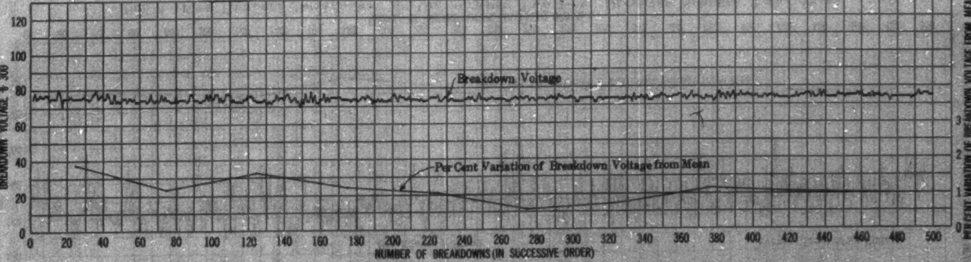

FIG. 6—FIVE HUNDRED BREAKDOWNS ON AIR BETWEEN TWO 2.54-CM. DIAMETER SPHERES 1MM. APART

between successive tests in oil are many times greater than the possible accuracy of breakdown tests in air, and that the cause of the variation therefore must be inherent to the material, the oil.

Comparison of the three oil curves in Figs. 1, 2, 3 and 7 shows that there is little difference between them. In other words, the erratic behavior of oil is not the result of the particular shape or size of the electrostatic field. The per cent variation between successive tests is a little less in a large sphere gap, and a little greater in a sphere and needle gap, than in a small sphere gap, but the difference is small compared with the difference between oil and air gap. In our former paper the point was made that with spheres in oil the actual breakdowns at the higher voltage fell below the breakdowns to be expected by the law of probability, possibly due to the approach to a true dielectric strength of the oil. The large sphere gap showed the same characteristics, while the sphere and needle gap gave a curve which was symmetrical on both sides of the mean, that is, apparently did not show this effect.

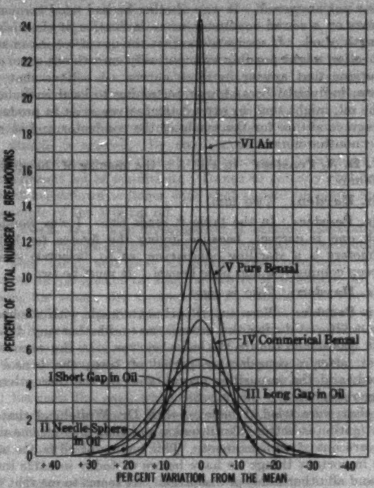

FIG. 7—UNIFORMITY OF DIELECTRIC STRENGTH

On the horizontal or x-axis is plotted the average per cent variation of the 500 breakdowns from their mean for each group. On the vertical or y axis is plotted the per cent of the total number of breakdowns. These six curves were plotted from the probability curves given mathematically below. The equations were determined from the test results. From the equations two of the curves are seen to have their peaks a little to the right of zero per cent variation. When reduced to a percentage basis and plotting as above, these curves were shifted back to zero for the sake of clearness. Each curve being an exponential continues on to infinity at each side but it is considered to represent the data in question only when the ordinate is more than one-tenth of the maximum ordinate or peak. This assumed range of limit of the probability law is marked on each of the curves by circles. Comparing the curves at these points it is seen that the air tests show variations from the mean no greater than 4 per cent, while the oil tests for instance show as much as 24 per cent variation. The equations follow:

Graph I —$y = 22.4\,\epsilon^{-.0051\,(x-3)^2}$
" II —$y = 20.7\,\epsilon^{-0.006\,x^2}$
" III —$y = 27.2\,\epsilon^{-0.0055\,(x-4)^2}$
" IV —$y = 45.8\,\epsilon^{-0.0251\,x^2}$
" V —$y = 60.8\,\epsilon^{-0.0536\,x^2}$
" VI —$y = 123\,\epsilon^{-0.232\,x^2}$

Examination of the two benzol curves, in Figs. 4, 5 and 7, shows that the variation between successive breakdown tests in benzol are materially less than in oil, especially so with chemically pure benzol, but nevertheless are still much greater than with air. Benzol therefore is intermediate in the uniformity of disruptive tests, between air and oil. Possibly this is due to the more uniform chemical constitution of benzol compared with oil.

Comparison of the two benzol curves shows that the uniformity of breakdown is greatly increased by the increased purity of the material. This suggests that the erratic behavior of oil may be due to the complexity of its chemical and physical structure.

The benzol curves were found to follow the law of probability both above and below the mean breakdown without showing any of the unsymmetry given by spheres in oil. With the same amount of energy back of the discharge the benzol seemed to carbonize much more rapidly than transil oil. Before testing, the benzol was, of course, transparent and colorless. After only 20 breakdowns it was opaque and black. Fig. 5 shows that during the first 50 breakdowns the dielectric strength decreased very greatly due to carbonization, and fell to less than half the initial value. After this however, additional carbonization of the benzol caused only gradual deterioration, no more than that of oil and the dielectric strength of the benzol containing colloidal carbon had become approximately constant. Fig. 4 shows that after refiltering, the benzol seemed to deteriorate slightly faster than at the beginning of the test.

The 500 breakdowns in air are seen to be much more consistent than even the benzol tests. As air itself is considered to have a definite and uniform dielectric strength these tests prove that the erratic behavior of the oil and even of the benzol greatly exceeds that which might be caused by the methods of testing, errors of observation, etc. That is, the comparative non-uniformity of the oil and benzol must be due to some inherent characteristics of the materials themselves.

On the probability curves of Fig. 7, the points where the probability has dropped to one-tenth its maximum value, have been marked by circles. While of course each probability curve as exponential extends to infinity most of the observed breakdown values are contained within the range of voltage between the maximum probability and the one-tenth value, and the width of the probability curve between the two circles of one tenth value thus offers the means of characterizing and comparing the different curves, with regards to their scattering of the breakdown values. Thus we get the following table, showing the range of the voltages over which the breakdown tests are scattered, in per cent of the mean value:

TABLE I

Percentage range of breakdown voltage, from mean:

Air	± 4 per cent
Chemically pure benzol	± 12 per cent
Commercial benzol	± 14 per cent
Oil	± 24 per cent

Table II shows a tabulation of the average per cent error that might be expected for (1) a single test, (2) three tests, or (3) six tests on oil if the mean of 500 successive breakdowns is taken as the correct dielectric strength and any variation from that as the error. It is seen that sphere-gap tests in air give an accuracy sufficient for their use for voltage determinations, especially when using the average of several observations, but that to get consistent results in the commercial testing of oil a gap should be so designed as to inherently average as many breakdowns as possible.

TABLE II

	Air	Long sphere gap in oil	Short sphere gap in oil	Needle sphere gap in oil
Single Breakdown Test		per cent	per cent	per cent
Average error	1.1	7.8	7.8	8.4
Maximum error	6.7	48.5	34.1	44.8
Maximum error except 3 readings	4.0	33.0	31.8	35.0
Three Breakdown Tests				
Average error	0.8	5.2	4.9	4.9
Maximum error	4.0	22.4	19.7	19.1
Six Breakdown Tests				
Average error	0.6	2.7	3.5	4.1
Maximum error	2.9	17.5	15.0	14.3

Discussion

W. A. Del Mar: I would like to ask the author why the successive tests were made on the same sample of oil. We have done a good deal of oil testing, and have always taken the precaution to pick out fresh clear samples for the tests. I am wondering whether more uniform results would be obtained if a fresh sample of oil were used for each test, than if you used the same sample five hundred times? It would seem that the matter of the chemical decomposition of the oil would enter into the problem, and that has not been mentioned in the paper.

E. D. Clarke: We have gone into the program of the testing of the variation and the breakdown of samples of oil, which seemed to be good oil. Quite an extensive investigation of the subject, which began some time ago and I would like to know how to eliminate some of the variation.

In this process we have raised the temperature of the quantity of oil to about 150 deg. fahr. gradually, and we have found that the oil then behaves quite uniformly.

Another thing is if the sample of oil be turned other side up, a few times, the values come out closely.

As to the point Mr. Del Mar brought up in this discussion, we have made a test with different samples from the same cup, and there was a very considerable variation.

John B. Whitehead: I think that these curves show a very encouraging uniformity, notwithstanding the large value that may be given to the extremes of variation; the authors have rendered a very material service in taking this large number of observations. It brings us to a point where it is possible, to specify the properties of oil in terms of a definite figure, and a maximum permissible deviation.

I think there will be little dissent from the conclusions of the authors that the irregularities are inherent in the structure of the material itself. When Mr. Hayden presented his last paper on the breakdown of oil, I ventured to ask a question, I believe he has not answered. It was whether he had tried corona as it appears on a round conductor as an indication of the dielectric strength of oil. It seems to me that the use of corona in such a connection might possibly automatically smooth out some of the variations that appear in these curves. I believe that using corona, individual breakdowns pertaining to local irregularities in the oil, might tend to extend themselves so as to produce an average condition for the whole of the conductor and so result in a smoother curve.

W. D. A. Peaslee: In Fig. 5 is the spacing of the spheres 2 or 20 mm.?

Mr. Hayden: Two mm.

Mr. Peaslee: In the table it reads two. I was wondering which one is correct, because giving the figures for both in millimeters is a startling comparison as to dielectric strength between commercial and pure benzol. It must be two.

Mr. Hayden: Two is right.

Mr. Peaslee: Were any experiments made with the heavier oil, not filtered during the process, as to whether any different result was shown than in the benzol curves. In the commercial benzol, after a considerable period of tests, the benzol was filtered, and the impurities precipitated by the disruptive discharge removed.

If that were tried, I believe, with Dr. Whitehead that this investigation is better than it looks, and that the extreme variations are not of such moment. This testing of oil is one of the most important things we have before us today in cable insulation and all other kinds of insulation. It seems to me that some of the results were tied up with the mobility of the three factors in the solution.

I would like to see some further work done on the filtering of the oil at different periods, to see if there is a section at which the rate of depreciation approaches the pure benzol curve, and in that case you will find, after the first 100 breakdowns, you are producing a constancy equal to that of air.

O. D. Wood: Designers have long realized the possibility of considerable variation in free oil spaces. For this reason, it has been the practise for years in transformers to break up with insulating barriers the oil ducts separating energized parts.

Solid insulation is not good when used alone, but oil separated by solid insulation in proper proportion gives the best cooling and breaks continuous paths, which may exist with free oil ducts or solid insulation.

The proper breaking up of the oil ducts with barriers tends to neutralize any unstable conditions that may exist in the oil. This is borne out by actual tests, an example of such tests made with oil spaces properly separated by barriers may be of interest. Free oil was separated by one, two and three insulating barriers. Tests were made with the barriers adjacent to each other, and alternating with oil spaces. The results obtained indicated a maximum variation of less than 10 per cent above and below the average value.

It is of interest to point out here, that although under certain conditions the dielectric strength of oil may vary over a very great range, in practise it has been made the most useful and reliable insulating material that is available.

J. E. Shrader: In air electrical discharges take place much more uniformly than in oil. The reason for this, no doubt, is the greater homogeneity in air than in oil. Then in studying the breakdown in oils one should examine it for non-homogeneity. I think that the most of us who have studied oils for their electrical properties recognize the fact that most of the non-homogeneity in oils is due to moisture. One speaker has stated that at elevated temperatures uniformity of breakdown is much greater. This is due to the fact that upon heating, moisture is removed and the oil becomes more homogeneous and not only is there greater uniformity of breakdown but breakdown occurs at higher voltages. Another cause of non-homogeneity is the presence of foreign materials such as lint and dust particles. The presence of these materials is deleterious the more because they take up moisture which may thus be concentrated in the strongest part of the electrical field, thus lowering the breakdown voltage. Barriers in electrical apparatus are of benefit because they prevent the lining up of these moisture laden particles.

In making successive tests upon a sample of oil the character of the sample is altered. By each breakdown moisture and impurities are removed so that at each successive breakdown we have a different set of conditions. Hence to get any real comparison of breakdown voltages each shot should be made upon a new sample of the original oil.

F. W. Peek, Jr.: The investigation of Messrs. Hayden and Eddy is very interesting in that a great number of consecutive points were taken and that all points were recorded. In a theoretical investigation of this nature it is desirable to use electrodes for which the stresses can be calculated. For this reason the sphere gap was used. With the electrodes and spacings used in practise the variation is decidedly less. However, the interesting fact is not the extent of the variation but that there is a variation and that it follows the probability curve.

It means that from time to time a chance variation occurs in the oil between the gaps which affects the dielectric strength. This variation, whether it is due to gas, or to the lining up of particles, has a considerable range. These tests, therefore, confirm, theoretically, the long established practise of using barriers.

C. P. Steinmetz: I had the advantage of seeing these results before their publication, and also of seeing a large number of other results which have not yet been published, and which, to my mind, seem to answer several of the questions raised.

To begin with the question whether new samples should have been taken. I have seen a large number of tests made by using new samples for from 25 to 50 tests, and from the results, I have to agree with Mr. Hayden that it is impracticable to do so, because the successive samples of oil from the same supply vary so much that constant or consistent results can be derived by using one sample only, but such a very large sample, several thousand cubic centimeters, that the individual breakdowns do not appreciably affect the oil. In these tests given here in the paper, I understand, Mr. Hayden took averages at every 50 successive breakdowns. These showed that for the first two hundred or three hundred tests there is no appreciable deterioration, but the breakdown voltage remains the same and only after that number of tests does the oil deteriorate.

Now, as to the different kinds of oil: I have seen tests of different kinds of oil, heavy oil and light oil, and water-white oil, but there was no appreciable difference in the nature of the tests.

The first thing that presents itself as possible cause of the erratic performance of oil, naturally, is occluded moisture. I have seen a number of tests made to find whether the moisture has anything to do with it. For instance, a sample of oil was taken and heated several times and the oil was then filtered by passing it through a large number of layers of hot filter paper, and then it was atomized into a high vacuum, and allowed to settle there, where certainly all occluded air and moisture was evaporated, and then allowed to settle under the exclusion of air for several weeks, and then it was tested again in the same way as oil taken straight from the barrel, but it did not show any materially higher nor more constant breakdown voltage.

A very curious result is shown by the curve of pure benzol. If you notice, there is a quite rapid deterioration during the first readings, and then it comes almost to a stand still, and the deterioration is less rapid. Now, benzol deteriorates very much more rapidly than oil, and while it started perfectly transparent, after fifty tests, it was entirely opaque, but it had become more constant, and a very highly carbonized black benzol was more uniform than the pure benzol. The curve of commercial benzol shows the same. After it was filtered, and a few hundred readings had been taken, the first part showed greater variability than after it became black. It is rather curious, and seems to show after you get it deteriorated and blackened, it becomes more constant again.

F. B. Silsbee: Some time ago I had occasion to participate in some tests of transformer oil for the American Society for Testing Materials[1] in which some 2000 breakdowns were involved. These were, however, distributed over a number of different conditions and consequently do not closely parallel the present work. It is interesting to note that the average deviation of 1 shot from the mean of a group of 50, as estimated from this A. S. T. M. data, comes out as 9 per cent which is in fair agreement with the present results. The earlier data also indicated, though much less emphatically, the astonishingly slight effect of the carbon formation on the breakdown voltage of oil.

One feature of interest in the present paper is the fact that in Figs. 1 to 4 inclusive there appear occasional very low points while there is an absence of corresponding occasional high points. This would presumably cause the frequency curves of Fig. 7 to be somewhat skewed as shown in the earlier paper by the same authors. It is is to be regretted that the experimental points are not shown on the curves of Fig. 7. Is it not probable that these low points are the result of a lining up of bits of impurity so as to make abnormally long weak spots in the dielectric much as suggested by Hirobe, Ogawa and Kubo?[2] These low points are strikingly absent in the case of pure benzol and air.

W. B. Buchanan: In his preliminary paper Mr. Hayden says that the discharge current was limited by the use of resistance in the low-tension circuit so that carbonization would be reduced to a minimum. Another important point is the length of time the arc is allowed to persist after each breakdown and as the method of controlling this is not stated, the system used in the Laboratories of the Hydroelectric Power Commission may be of value.

Our regular testing equipment is provided with an overload relay in the primary circuit thus opening the circuit much more quickly than can be done by hand. The relay does not operate on incipient sparking such as occurs when fine dust, etc. is present but can be depended on to open the circuit promptly as soon as actual break down value of the oil itself is reached. The voltage control is obtained from a motor-driven potentiometer rheostat, one coil closing the circuit automatically at zero voltage, another opening it on puncture of the oil. With this equipment we believe our oil test results are more reliable than is normally obtained by hand control and from a mental summary of the results obtained the writer would say that good oil which has been in service for some time and well taken care of may show a peak on the probability curve of the test results which would be comparable with that shown by Mr. Hayden for air. On the other hand new oil is nearly always more erratic and quite frequently the breakdown value as shown by the meter does not tell the complete story. Deductions may be made sometimes by noting the behavior of the oil itself under stress previous to breakdown as to whether the possibility of improving the oil by further filtration is promising or otherwise.

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[1] Report of Committee D-9, A. S. T. M. on Electric Insulating Material—June 1921.

[2] Hirobe, T., Ogawa, W., and Kubo, S. Report No. 25, Electrotechnical Lab., Tokyo, Japan.

W. S. Flight:

1. *General:*

This investigation has shown (a) That provided reasonable precautions are taken in determining the breakdown voltage of air fairly consistent results may be obtained. (b) When determining the breakdown voltage of certain liquid dielectrics it is impossible to obtain anything like as consistent results as with air.

It would appear that from Hayden and Eddy's investigations and also from other published data[3], that the mechanism of breakdown of liquid dielectrics (particularly that of oil of commercial purity) is different from that of gaseous dielectrics.

2. *Theory of Breakdown of Oil:*

From an examination of the present available data relating to the electric strength of oil it would appear that oil of commercial purity may breakdown in two different ways. (a) *When Tested between Point Electrodes*: by actual puncture through the dielectric in a similar manner to gaseous dielectrics: the action of the electric field being rather to repel than to attract any impurity into the gap. (b) *When Tested between Sphere Electrodes*: by the lining up of impurities which either shorten or entirely bridge across the gap. (c) *When tested between Disk Electrodes*: by a combination of methods (a) and (b).

(3) *Experimental Evidence in Support of the above Theory:*

(a) *Breakdown of Oil between Point Electrodes*: (i) *Results reported by the Electrical Research Assn.* The data given in Table I below have been abstracted from Table I on page 702 of the "*Electrician*" for December 2, 1921.

TABLE I

Investigator	½ in. sphere gap 15 mils apart	Point gap 15 mils apart
Digby & Mellis....................	11.5 kv.	17.5 kv.
Everest....................	20.0 "	22.0 "
Peek....................	64.0 "	22.0 "
Hirobe....................	92.0 "	15.0 "

These tests on oils containing different quantities of impurities as well indicated by the sphere gap tests, showed that the results obtained with point gaps were practically uninfluenced by the impurities in the oil. (ii) *Results reported by Dr. Hirobe*: In report No. 25 of the Third Section of the Electrotechnical Laboratory of Tokyo, Dr. T. Hirobe gives a curve showing the relationship between the moisture content and the breakdown voltage of fibre-free oil tested between point and disk. During these tests it was found that for a considerable range the breakdown voltage *increased* with increase in the moisture content. An indication of the numerical value of this increase can be obtained from the result given in Table II below.

TABLE II

Effect of Moisture Content of Oil on the B. D. V. of Fibre-Free O'', when tested in a 300-mil gap between a point and a disk

Percentage of moisture in oil	B. D. V. at air temperature	Percentage *increase in* B. D. V. over that of moisture free oil
Nil	21 kv.	Nil
0.004	25 "	19
0.008	37 "	76
0.012	45 "	114
0.020	52 "	149
0.028	52 "	149

The increase in B. D. V. with increase in moisture content is explained by Dr. Hirobe to be probably due to the following: (a) That with pointed electrodes the electric field is not uniform and consequently the moisture cannot line up between the electrodes and form conducting chains. (b) That particles of water collect around the electrodes and by changing the shape or area of the point so reduce the maximum voltage gradient between the electrodes.

(b) *Breakdown of Oil between Sphere Electrodes*: (i) *Results Reported by Dr. Hirobe*: In the same reference as given in (a), (ii), Dr. Hirobe shows a corresponding curve obtained with the same oil but with ½ in. sphere electrodes and a gap of 150 mils. Both with fibre-free oil and oil containing fibres the electric strength was found to *decrease* with increase in moisture as shown in Table III.

TABLE III

Effect of Moisture Content of Oil on the B. D. V. of Fibre-Free Oil and Oil Containing Fibres, when Tested in a 150-mil gap between ½ in. diameter spheres.

Percentage of moisture in oil	B. D. V. at air Temp.		Percentage *decrease* in B. D. V. over that of moisture free oil	
	No fibres	With fibres	No fibres	With fibres
Nil	90 kv.	35 kv.	Nil	Nil
0.004	71 "	20 "	21.0	43.0
0.008	66 "	16.5 "	26.6	53.0
0.012	64 "	16 "	29.0	54.0
0.020	62 "	15.5 "	31.0	55.8
0.028	61 "	15.5 "	32.4	55.8

The fact that the presence of fibres causes, with a definite moisture content, a greater falling off of electric strength than when the fibres are not present, is attributed by Dr. Hirobe to the following: With sphere electrodes and a comparatively short gap the electric field is fairly uniform, and when fibres were present in the oil these were observed to line up across the gap, and if of lower electric strength than the oil itself, breakdown took place at a lower voltage. When water was introduced into the oil a small percentage was apparently dissolved in the oil and caused a certain decrease in the electric strength. The greater part of the moisture however, was held in suspension in the form of minute spheres, which, due to their high surface tension, were not distorted by the electric field and so could not of themselves form conducting chains across the gap. When fibres were present in the gap, the water was absorbed by the fibres, which on bridging across the gap thereby produced a greater falling off of the breakdown voltage.

4. *Tests on Oil of Lower Purity.*

In attempting to apply the theories outlined in Section 2 above to explain the results reported by Messrs. Hayden & Eddy, it must be remembered that as these investigators' oil was first rendered as free as possible from moisture and other impurities the electric strength was considerably higher than oil of commercial purity. For example the average breakdown voltage of the oil when tested between 1-cm. spheres and with a 2-mm. gap was 55 kv. whilst the American practise in industrial work is to accept oils which have a breakdown voltage of 22 kv. when tested between 1 in. diameter disks and a 0.10-in. gap, and the British practise is to accept oils having a breakdown voltage of 22 kv. when tested between ½ in. diameter spheres and a 0.15-in. gap. It is probable that with oils of commercial purity distinctly different results may be obtained, and it would appear well worth while to extend this investigation to cover oils of lower purity.

With the latter it is probable that considerably more erratic results would be obtained when the electrodes consist of a sphere, and more uniform results when the electrodes consist of a point and a sphere.

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[3] See the following:

(a) Electrical Insulating Properties of Transformer Oil, by Dr. T. Hirobe. Report No. 25 of Elec. Tech. Laboratories Tokyo, Japan.

(b) Effect of fibre on the electric strength of insulating oil, by T. A. McLaughlin, Electrician.

(c) Research on Insulating Oils by the Electrical Research Association, *Electrician*, December 2nd, 1921.

It is interesting to note that even with the comparatively pure oil employed by Hayden and Eddy it was observed that the point electrodes gave the most consistent results, and also that with the point electrodes the curves between the percentage variation from the mean and the percentage of the total number of breakdowns was symmetrical on both sides of the mean.

5. *Effect of Viscosity:*

If, during the determination of the electric strength of liquid dielectrics the conditions are such that breakdown takes place due to lining up of impurities, the freedom with which these impurities can move about in the oil should have an effect upon the breakdown voltage.

Reducing the viscosity of a liquid dielectric may affect the breakdown voltage by (a) Increasing the ease with which the impurities can line up. (b) Increasing the velocity of the circulating currents in the oil which are set up by the electrostatic stress on the liquid adjacent to the electrodes.

The writer has shown elsewhere[4] that decrease in viscosity may under certain conditions cause an increase and under other conditions a decrease in the breakdown voltage of a liquid dielectric. It is possible that the more consistent results obtained with benzol may be due to the fact that this liquid had a lower viscosity than the oil employed. To study the effect which viscosity may have in this connection, it would be interesting to have similar data to that obtained by Hayden and Eddy on transil oil at, say 90 deg. cent.

W. N. Eddy: A large majority of the questions brought up in the discussions is very well answered in the discussion of Dr. Steinmetz.

We understand Mr. Buchanan to say he has obtained breakdown data on oil that are no more erratic than our data on air. We must admit that we are inclined to question the testing methods giving such radical results. After examining the rather brief description of his testing methods we believe we at one time tried out a similar scheme and discarded it as being too insensitive.

Mr. Flight suggests that the difference shown between oil and benzol might be due to the difference in viscosity, and that this could be brought out by taking similar data on oil at 90 deg. cent. We have taken several similar sets of data on both the same and much lighter oil at 100 deg. cent. and the results while possibly a trifle more consistent than our published oil data were in no way comparable with those on benzol.

J. L. R. Hayden: Answering some of the questions which have not yet been answered, we wish to say:

We have made tests of oil at different temperatures, up to 110 deg. cent. but have found no material difference in the lack of uniformity of successive tests. Neither did we find any material increase of uniformity by removing the moisture by heat and high vacuum.

We have made a number of successive tests on oil without previous filtering, and after filtering; we have made tests on the oil carbonized by a large number of disruptive tests, and on the latter oil after filtering off the carbon, but have found no material difference in the erratic variation of successive tests, though the average value of the breakdown strength was increased by filtering, and lowered by carbonization by previous tests. It therefore seems that the lack of uniformity is inherent in the oil as such.

We have not yet made any extensive tests on corona effects in oil, but our experience thus far is that there is no real corona formation in oil, but the appearance of visual corona is coincident with dissociation and gas formation, and what corona appears, is in the gas bubbles, but not in the oil. When this occurs, the results become still more erratic, as may be expected from the formation of gas in the discharge gap.

As regards to the lengthy discussion by Mr. W. S. Flight, while we do not agree with all his conclusions on the mechanism of breakdown, we came to the conclusion that the breakdown of oil between needle points is different from that between spheres. But this conclusion is not new but had been reached by Mr. A. B. Hendricks of Pittsfield, in an extended investigation on oil made some years ago, which led to the development of the present disk gap, standardized now for commercial oil testing. Mr. Hendricks found that the indications of the quality of oil by the point or edge gap do not parallel those of the sphere gap, but sometimes the point gap shows variations in quality better, sometimes the sphere gap. Neither gap therefore is most satisfactory for all conditions. This has led him to the development of the present disk gap for commercial testing, as a combination of a uniform field, between the flat disks, analogous to the sphere gap, and a point or rather edge gap, between the edges of the disks, showing the character of the point gap.

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[4] See Spark Over Voltage Through Oil, *Beama Journal*, Feb.-March, 1922.

Control of Gaseous Conduction

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Review of the Subject.—*In electric circuits of all sorts, power is transmitted principally by metallic conductors. In order to control the flow of power, or to convert it from one form to another, the constants of the circuits are varied. The connections of the metallic conductors may be altered for this purpose; but on high potentials this operation is attended with difficulty. The rapidity and ease of control are also limited.*

For this reason there has been a tendency, in recent years, toward the increased use of control devices employing non-metallic conduction and these are now being rapidly brought to the fore. As examples we have the very versatile thermionic tube and the mercury arc rectifier. The former has received particular attention of late.

Devices employing conduction by gaseous ions have been handicapped in this general evolution by three main disabilities: the first being the difficulty of placing the discharge where wanted, the second, the tendency of the working gas to disappear, and the third, decidedly erratic action. These disabilities have recently been to a large extent removed by the advent of a principle called the "short path principle", by which discharge can be prevented except where wanted. This has also led to long life, for by placing the discharge in proximity only to certain porous materials, gaseous clean-up and disintegration are both prevented. With this change, uniformity of action also appears.

By utilizing this principle, gaseous conduction devices may be designed, for example, as rectifiers. Two examples are described, the first obtaining unilateral characteristics by the use of a magnetic field, and the second by the use of a space charge.

The present models, as described are capable of handling only small amounts of power; but there is no inherent limitation in this direction. The usual conditions of cost, reliability, life and so on will determine development for higher powers.

It is impossible to predict at present the particular portions of the electrical field in which this device in its various forms will find a use. The authors believe, however, that engineers will find its possibilities of interest.

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I. CLASSIFICATION

THERE is a very noticeable tendency in present-day electrical engineering toward the use of control devices which may be generally specified by stating that they involve non-metallic conduction. It is difficult to control the flow of current in a wire by any control device which does not actually separate the metallic circuit. A small amount of control can be obtained by magnetic fields, but this is entirely inadequate for most power purposes. On the other hand, the flow of current through devices which involve other types of conduction may be much more readily controlled by external means. This gives rise to a host of devices, for the control of current makes possible the construction of rectifiers, amplifiers, and the like.

In present-day power engineering there is great need for better rectifiers for railway work and so forth, and for better control devices for handling in reasonable space the large voltages and currents necessary in extensive power systems. Undoubtedly the next few years will see a rapid development of devices for these purposes. The probability is that much of this development will occur along the lines of non-metallic control.

Devices which utilize non-metallic conduction may be readily classified according to the nature of the carriers of electricity which are employed.

1. Devices employing ions in a liquid or semi-solid: Insulators which become conducting because of high temperature and electrolytes in general involve this type of conduction. Such conduction is always accompanied by chemical action. No devices involving this type of conduction have become commercially important as rectifiers or the like. The aluminum lightning arrester is an example of a protective device operating on this basis.

2. The simplest type from a theoretical standpoint is that in which electrons only are used. The device then consists of a container exhausted to a hard vacuum, with two or more electrodes, one of which is a source of electrons. Such a device is the thermionic tube, the most important single piece of apparatus which has appeared in electrical engineering in twenty years. In addition to the thermionic tube, various other similar arrangements have been suggested in which the supply of electrons is obtained without utilizing an incandescent member, as for instance by the use of the photo-electric effect. None of these latter are at present commercial.

Devices under this classification are characterized by somewhat severe current limitations. The internal drop is very variable, and is determined by space charge effects. They are capable of operating at very high potentials.

3. Devices employing electrons, and gaseous ions:

(a) Under this heading we have first the device which employs a hot filament in a gas-filled receptacle. Such for instance is the Tungar rectifier. This device conducts relatively large currents, for it employs gaseous conduction as well as conduction by means of the primary electrons evaporated from the filament.

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t is, however, unable to withstand large reverse potentials.

(b) Under this heading there have been second many devices in which the supply of electrons is obtained in other ways than by heating a filament. The principal way is to remove them from a cold metal electrode by positive ion bombardment. The old "Geissler" tube operates in this manner. So also does the gaseous X-ray tube. Such devices offer great possibilities, but have not heretofore become important commercially as control devices on account of difficulties which will be treated below. Under this heading comes the device which is the subject of the present paper, and this class will be further analyzed.

4. There are also devices in which the carriers are electrons, gaseous ions and charged metallic vapor. This includes all sorts of arcs. The mercury arc rectifier comes under this heading; and as an example of its use as a control device, the Vreeland oscillator.

This type of conduction is accompanied by rapid vaporization of the electrodes. The part played by the vapor in the conduction is still a matter of doubt. The material of the electrodes is transferred and lost, so that it must be continually replaced. In mercury arc devices this replacement is made automatic. Devices of this type are characterized by low internal drop, and the current capacity limited only by the cooling means employed. In voltage they are limited to that potential which will cause ionization of the working gas and conduction from the cold electrode.

II. ANALYSIS OF TYPE 3 (b)

The type of device employing electrons and gaseous ions in which the electrons are obtained by bombardment, has many desirable features. First, the current which can be passed through such a device is limited only by the capacity of the cooling means employed to dissipate heat. For short intervals there is hence practically no upper limit to the amount of current which can be passed between the electrodes. This is in contrast to the thermionic device, in which the upper limit of current is dependent upon the number of electrons which can be evaporated from a filament. In this respect the gaseous conduction device and the arc are similar.

Second, there is not necessarily involved any part at very high temperature. This greatly simplifies design and removes one limitation to the life of the device.

There is no inherent reason that disintegration of electrodes should accompany gaseous conduction proper. Where disintegration enters in such a device it is incidental and avoidable; for the operation does not depend upon and is not necessarily accompanied by disintegration. This feature is in direct contrast to both the thermionic tube and the arc. In the former the filament, in order to emit electrons copiously must unavoidably operate at such temperature that molecules of the material of the filament also evaporate to some extent. The filament life is thus directly connected with the quantity of electricity passed through the tube. In the arc the wasting of the electrodes is also intimately involved in the mechanism of conduction, and is here much more rapid; although it can be avoided in the mercury arc, and to a lesser extent in other arc devices, by provision for replacement.

On the other hand, gaseous conduction devices have always in the past been subject to very decided limitations.

First, the voltage which could be employed has been limited by the gas pressure used. In this respect there has been for this type of unit, in common with the arc a serious disadvantage as compared to the thermionic tube. The disadvantages ordinarily present in this class of device in general, and this disadvantage in particular, are treated in detail in this paper.

Second, the internal drop is in general of necessity higher than in the arc. A comparison of internal drop with that of the thermionic tube is hardly possible, for the gas tube involves a drop nearly independent of the current, while the exact opposite is true of the thermionic device.

Third, gaseous conduction devices have been uniformly erratic in action. The reason for this will be brought out below. On this account, knowledge of the theory of gaseous conduction has been delayed, and experimenters have been repelled from this field. The limitation is not inherent, but has always been present.

Fourth, this class of apparatus has been liable to short life on account of a change in the nature or pressure of the gas employed, or due to a variation in the electrode surface. This last disadvantage is decidedly avoidable, but it has been the principal obstacle in the past to development along these lines.

This paper is devoted to the brief exposition of a development by which the disadvantages of this type of device have been largely overcome. By removing the difficulties, the way has been prepared for a number of applications of the principles of gaseous conduction. One of these applications is described sufficiently to render the use of the principles apparent.

III. THE SHORT PATH IDEA

The first limitation was in the working voltage (or the back voltage in a rectifier) which could be employed. In the ordinary gas tube this is limited to that voltage which will cause ionization of the gas and release of electrons from the electrodes by bombardment at times when the device should really be insulating. There has been recently developed a principle which allows of the use with the gas conduction tube of voltages far in excess of this limit.

This principle is properly called the "short path principle". It is the outgrowth and extension of an observation which has long been noted by physicists. It allows of the use of high back-voltages by not giving them opportunity to produce ionization.

It has long been known that if two electrodes are situated in a gas of a pressure such that their distance apart is comparable with the mean free path of an electron in the gas, a discharge will pass between them by long paths in preference to shorter ones. If two electrodes are spaced close together in a large bulb in a properly attenuated gas, the discharge between them will prefer the long path from the back of one electrode clear around to the back of the other, the short direct path remaining dark. It has not been generally recognized how strong is this preference, or that it could be utilized to advantage. The short path idea extends this principle by suppressing the long path entirely. If we so construct the device that *all* paths between the electrodes available for discharge are short, the device will stand large voltages and carry practically no current. All paths may be rendered short, as above defined, either by placing the electrodes close together or by placing obstructions in the way of the discharge. The diagram of Fig. 1 will show one manner in which this can be accomplished. It will be noted in this diagram that, if the electrostatic field between the electrodes be mapped out, all lines of electrostatic force are either short or are interrupted by the glass of the containing tube in such manner that the path available for discharge is short. When a potential is applied to such a device, there is no conduction even far above the potential at which the device would break down if the electrodes were widely separated, or the gas pressure high. As an illustration of this statement, a device constructed as above with clean electrodes and pure gas, with a spacing of one millimeter and a pressure of two millimeters of helium, will withstand continuously 10,000 volts and pass an amount of current which is hardly measurable. With the electrodes several centimeters apart, this same tube would have broken down at perhaps 300 volts, and at 500 volts applied would have carried several hundred amperes, if the external circuit would allow, and would probably have been destroyed. It should be noted carefully, however, that in order to render the unit thus insulating, under conditions where widely spaced electrodes would break down, it is necessary that *all* paths available for conduction be short.

By properly utilizing this principle, the voltage limitation of the gaseous discharge type of conduction is largely removed.

IV. FIRST APPLICATION OF THE SHORT PATH IDEA

The short path idea also removed the third limitation. It can render a gaseous conduction device stable and reproduceable instead of erratic in action.

Gaseous conduction devices have in the past almost always been constructed in glass tubes and with the diffuse discharge intimately in contact with the glass. Such construction is sure to lead to erratic behavior. Due to the ionization, the glass is bound to accumulate charge, which will vary rapidly with the nature of the discharge, the temperature of the glass and a number of other factors. These charges vary the electrostatic fields present, and modify the conduction in a sudden and arbitrary manner. Due to this factor alone, such devices have gained an undesirable reputation as regards unreliability of action. It is evident that in order to remove difficulty in this regard, the discharge must be confined to a part of the device remote from any insulator.

This can now be accomplished. By the short path idea, ionization is prevented everywhere in the device except in one region where the paths are left long or are rendered so. This region is located far from any insulators. Charges therefore cannot accumulate. The resulting discharge is steady.

One means of arranging matters is shown in Fig. 2. The tube here shown is similar to the insulating tube of Fig. 1, except that one of the electrodes is made hollow and a central opening to this hollow space is provided. Between the electrodes in the center there are hence long paths. So when a potential is applied, a discharge can occur in this central region and nowhere else. Such a discharge is remote from the glass of the tube or from any other insulator. It is thus not affected by parasitic charges, and is steady in accordance with the circuit conditions.

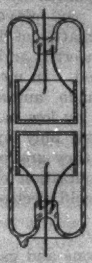

FIG. 1

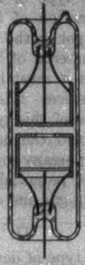

FIG. 2

As an example of this steadiness may be mentioned a tube carefully constructed along the lines shown in Fig. 2. A current of about ten milliamperes was passed through this tube from a storage battery source. A pair of high-resistance telephones placed in series with the tube gave no sound. In fact the variations in current were amplified by a two-stage thermionic amplifier before becoming barely audible. This is in decided contrast to the result which would have been obtained had the electrodes been widely separated and the discharge in proximity to the glass walls.

Nearly all of the study which has been made of the laws governing gaseous discharge has utilized glass-walled tubes with the discharge in proximity to the glass. To this fact may be attributed much of the present lack of complete knowledge of these laws.

V. THE MAINTENANCE OF GAS PRESSURE

The same control of the discharge which is used to render it stable may at the same time be used to avoid the last disadvantage mentioned in the analysis. This limitation involved the disappearance of the working gas.

The variation in pressure which occurs in the usual gaseous conduction apparatus has long been a source of difficulty. It was one of the principal drawbacks of the gaseous X-ray tube; and it has to a large extent prevented the rapid development of gaseous discharge illumination.

When a discharge is passed through the ordinary gaseous discharge tube, the nature and pressure of the gas continually change. Of course when the working gas is chemically active, the disappearance is readily accounted for. Even when using an inactive gas, such for instance as helium, a variation in pressure will occur. There will, for one thing, be a variable amount of gas occluded on the walls of the container, but the change in pressure from this cause is small when any fair-sized amount of gas is present. In addition, however, there is a continual and really serious disappearance of the gas due to another phenomenon entirely. In order to make a gaseous device of long life, this effect must be avoided. This disappearance is not due to chemical action, as it continues even when the working gas is chemically inactive.

A study, made possible by short path control, has determined the action of this second cause of disappearance and has found a remedy.

The action of clean-up of a working gas which is chemically inactive is usually accompanied by disintegration. In any case the presence of disintegration greatly increases the rapidity with which the working gas disappears. The amount of gas which can be removed from a vessel in this manner is truly surprising. By passing a discharge between aluminum electrodes in a half-liter vessel, for example, the gas pressure of helium has been reduced from seven millimeters to practically zero in a few hours' time. In fact, quite a hard vacuum may with care be produced in this manner.

Apparently gaseous discharge is accompanied by a penetration of the impacting positive ions into the cathode. The distance to which they can penetrate in this manner must be extremely small, under ordinary conditions of the order of magnitude of one-ten-thousandth of an inch. Yet very large volumes of gas may thus disappear. If we compute the gas pressure produced in this manner at the surface layer of the electrode material, it is found to be enormous. This possibly forces gas further into the interior of the metal progressively. It also results in minute explosions which project small particles of the metal from the electrode at high velocity. This is at least part of the mechanism of electrode disintegration. This disintegration is accompanied by gas disappearance.

One or two observations will tend to throw light on the above statements. First, the gas which disappears in this manner can be in great part recovered by heating the electrode material to near its fusing point, thus apparently offering the imprisoned gas opportunity to escape. The temperature necessary for recovery therefore depends upon the material of the electrodes. This has been accomplished with several different materials.

Another observation is more striking. A tube was constructed as shown in Fig. 3. In one electrode was located a small volume of pure tin. In fact the lower electrode, of iron, was coated all over inside with the tin. The discharge is confined by reason of the short path principle to such space that one electrode is in effect entirely of tin. The device was also constructed so that during discharge the surface of the tin could be observed by means of a low-power microscope. The tube was then operated at a current such that the electrodes became sufficiently warm to render the tin molten. Under these conditions a very interesting phenomenon was observed. Small bubbles appeared on the surface of the tin, gradually increased in size and finally burst. The bursting was accompanied by the projection of a small amount of metallic tin at fairly good velocity. Some of these bubbles were large enough to be observed with the naked eye, although their size depended naturally on the temperature and hence the viscosity of the tin. Moreover, it was observed that with the discharge thus confined to tin electrodes in this molten state, there was no change of the pressure of the working gas over long intervals of time of discharge. Intervals were studied of several thousand hours and with 100 or 200 milliamperes flowing. It thus becomes very apparent that disintegration and gaseous clean-up go together. Also that by proper construction, difficulties of this nature can be entirely avoided.

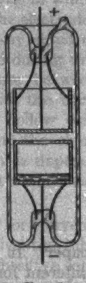

Fig 3

As an additional method of attack, it has been noted that a discharge maintained in proximity to carbon, and to nothing else, will not result in a disappearance of the working gas, provided the carbon is of proper grade and the working gas is chemically inactive. This is also true of some other materials under definite limitation as to allowable voltage drop and so on. The use of carbon, however, will serve as an excellent example. Apparently carbon does not disintegrate appreciably under a discharge of reasonable voltage drop, for tubes with carbon electrodes operated over periods of several thousand hours showed no measureable change in the carbon surface. This is due undoubtedly to the porosity of the carbon, which prevents a gas pressure from accumulating. Carbon will not hold the working gas imprisoned.

There is still room for a great deal of investigation on the subject of gaseous clean-up. The above procedure will enable us, though, to construct devices of this nature in which any limitation of life due to disintegration, or loss of working gas, is entirely avoided as far as can be determined from tests extending over more than 6000 hours on two of the specific constructions outlined.

VI. Magnetically Controlled Tubes

By utilizing the above principles, we now have available a type of gaseous discharge device which is capable of withstanding a high voltage, which is stable in operation and which is of long life. There is immediately a large number of ways in which such a device may be controlled and utilized. One of these and its application will be described in the present paper. In a previous paper[1] has been described a different form, which need here only be mentioned.

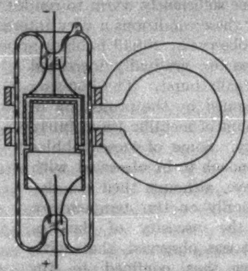

Fig. 4

In the form of device described in the previous paper a construction is utilized such as is shown in Fig. 4. The electrodes consist of two concentric cylinders. The gas pressure employed is such that the distance apart of the cylinders is short compared to the mean free path of an electron in the gas. *All* paths between the electrodes are rendered short by the construction shown. Under these conditions the device insulates for a fairly high potential applied in either direction.

Provision is made, however, for the introduction of a magnetic field which is nearly axial in the space between the electrodes. This is accomplished by means of a permanent magnet and pole pieces, as shown, whereby the field is conducted to the space where it is desired. Without the presence of the field, the flight of electrons between the cylinders is radial. By the action of the field, these paths are curved. A curved path between the cylinders is long compared to the direct radial path. Accordingly the device may be so arranged that, with the field present, the electron paths are long enough to cause cumulative ionization and consequent conduction, whereas without the field we have complete insulation.

Under these conditions the strength of field necessary for conduction with the inner cylinder negative is greater than that for conduction with the outer cylinder negative. In fact, the ratio of the two critical fields is the same as the ratio of the cylinder diameters. This relation, which was first derived from the mathematics of the electron paths, has been checked by experiment. Accordingly, by utilizing a field strength intermediate between these two values, a device may be produced which will conduct in one direction only; that is, a rectifier.

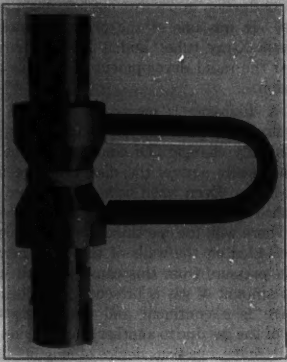

Fig. 5

Fig. 6

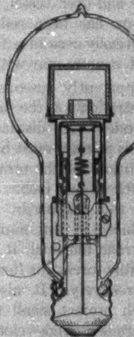

Fig. 7

Illustrations of a tube of this type are shown in Fig.

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[1] *Proceedings* of Inst. of Radio Engineers, February, 1922.

5 and Fig. 6. The magnet and pole pieces are removed in Fig. 6 in order to show the construction. It will be noted that the tube is made cartridge type, with ferrules to be inserted in clips similar to fuse clips.

Certain quite important benefits as regards allowable voltage range and allowable variation of field strength may be obtained by arranging the magnetic field to be somewhat curved and of non-uniform strength. These matters need not be entered into at the present time.

The above method of control, by means of a magnetic field may, of course, be used for other purposes than that of producing rectifiers. By utilizing a tube in which the design is adjusted to render it critical to field strength, an amplifier may be produced. Also, by any of the usual schemes of "coupling back," such an amplifier may be made to act as an oscillator.

The magnetic type of tube is thus capable of a variety of uses. As a rectifier constructed with carbon electrodes of special composition and with one of the inactive gases, it has an internal drop of about 150 to 200 volts. The efficiency is therefore high on rectification of voltages of a few thousand. The current which can be passed through such a tube is limited only by the amount of heat which can be dissipated from the surface of the tube. Hence its power output is limited only by its design, and not by any inherent current or voltage limitations.

VII. Hollow Cathode Type of Rectifier

There are other types of control possible besides magnetic control. One of these is to use a space charge effect, the space charge being due principally to the positive ions. By the use of this principle, rectifiers may be produced which, while they do not have the versatility or all of the power possibilities of the manetically controlled tube, are yet preferable for some purposes on account of simplicity.

A cross-sectional diagram of one such tube is shown in Fig. 7. It will be noted that the cathode consists of a hollow carbon cup. The anode consists of simply a carbon button placed directly in front of the hole in the cathode. By the use of shields, all paths between anode and cathode, except those through the hole, are rendered too short for conduction at the gas pressure used. There is no magnetic field, and no auxiliary control device of any sort. Only two connections are made to the tube.

The principle by which this device operates is somesomewhat involved. A brief outline only will be presented here. In general, it may be stated that the action depends upon the wide difference between the mobility of electrons and positive ions, and upon the accumulation of a positive space charge.

When the device is conducting current, the space inside the cathode is filled with ionized gas, that is with a cloud of electrons and positive ions. It is due to the presence of these, and to their wandering toward the anode and cathode respectively, that conduction takes place. At any given instant, however, there will be a very great preponderance of positive ions. This is due to the much greater mobility of the electron. The charges on electron and singly ionized positive ion are equal. Their masses are, however, in the ratio of one to several thousand, the exact ratio depending upon the nature of the gas used. Accordingly under a given applied potential gradient, the electrons as they are freed acquire velocity and move out of the field with much greater promtitude than the positive ions. The slow-moving, heavy ions are left behind. Accordingly we have ordinarily in gaseous conduction devices, during conduction, in the space between anode and cathode a positively charged cloud.

Due to the form of the electrodes in the hollow cathode type of *S*-tube, the potential gradient in the hollow space inside the cathode is normally small. The cloud of positive ions is hence swept out of the field only slowly. Due to this fact the cloud is not cleaned up or discharged during the half-cycle in which no current flows through the device. If the electrodes were simply placed opposite each other, any cloud of positive ions would be completely removed during this inactive period if the potential difference between electrodes, which during this interval equals the back voltage on the rectifier, were high. The hollow construction prevents this from occurring, and the cloud of ions on which the operation of the device depends persists from cycle to cycle, when used at commercial or higher frequencies.

Refer to the simplified diagram of Fig. 2 for convenience. When the hollow electrode is negative, the tube conducts freely. Under these conditions positive ions are dropping from the cloud onto the interior surface of the hollow cathode, where they liberate electrons. These electrons proceed toward the anode, and on their way ionize neutral gas molecules and form new positive ions, so that discharge is maintained. The original electrons and those formed by ionization nearly all pass out sooner or later through the hole in the cathode, and thus reach the anode; which latter for this direction of conduction is the solid electrode. This they can do rapidly and with facility on account of their great mobility, which allows them to attain speed quickly. Thus conduction in this direction occurs with facility.

Consider now, however, that the potential is applied in the reverse direction, the solid electrode being now the cathode. Positive ions under this condition will wander out from the hollow space, through the hole, and impinge upon the solid cathode. Their progress for most of their journey is, however, painfully slow; for they are large and heavy and the gradient of the field up inside the cloud is extremely weak. Nearly all the potential drop, because of the geometrical construction and the space charge effect, occurs out in the region between the electrodes. Practically the only ions acted upon by the potential are those near the exit. When an ion reaches here it speed up, drops into the cathode, and there may release an electron. This electron flies back into the cloud, and possibly produces ionization. The current that can pass is, however, limited to that produced by the number of ions arriving at the cathode; and this, on account of the conditions, is very small for potential in this reverse direction.

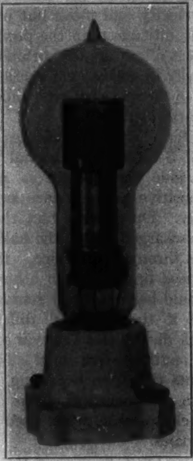

FIG. 8

For potentials in the conducting direction, the cloud of ions forms practically an extension of the anode projecting up into the hollow space inside the cathode. A large area is available, and a steep gradient, to pull ions over to the cathode and cause conduction. For a potential in the reverse direction, the cloud of ions serves again practically as an extension of the anode, in this case the hollow member, but now it acts effectively to plug up the hole in this electrode and render all possible paths for conduction substantially short. The area acting is small, and very few ions are pulled to the cathode to cause current.

The ratio of currents for the same applied potential in the two directions, when that potential is sufficient to cause conduction at all, is much greater in the working range than the ratio of the two cathode areas; the first being the inside area of the hollow electrode, and the second the projection of the hole onto the solid member. The ratio is much greater, for in one case conditions are correct for building up cumulative ionization and in the other case they are not.

There are secondary additional actions going on, such as recombination etc., which complicate the analysis. For example, when the tube is first started, there is a transient period during which the cloud of ions is being built up. The above does not pretend to be complete, nor entirely rigorous. It will, however, give some idea of how such a hollow cathode device, controlled by the presence of a space charge, utilizes the short path principle for rectification.

Tubes constructed in accordance with this principle are shown in the illustrations Figs. 8 and 9, and in section in Fig. 7. These tubes are constructed for low-power service where simplicity and long life are essential requirements. All that is necessary in order to connect them into circuit is to screw them into the ordinary lamp socket. Of course where higher potentials are desired, the socket must be made special in order to properly withstand the voltage.

This tube is exactly the same in principle as the simplified tube of Fig. 2. The additional parts employed are for several purposes. It is now being produced for engineering use, is arranged to be mounted on a single stem, which makes for accuracy and ease of assembly. Both leads are brought out from the same end, which is convenient in moderate voltage service. The working parts are far removed from the glass bulb, which avoids danger of overheating the glass. There is a considerable volume of reserve gas, which avoids sudden changes of gas density due to temperature effects.

The tube of Fig. 8, as now supplied commercially, has a rated capacity of 50 milliamperes, and is designed to be used for supplying 500-volt direct current. In both of these matters it has some overload capacity. This particular tube was designed for the use of amateur radio enthusiasts for supplying plate voltage for use on their thermionic tube generators. It is also useful for charging small storage batteries, for fire alarm systems, and so on.

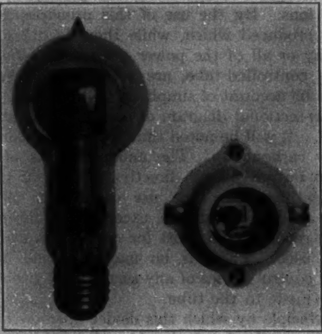

FIG. 9

The behavior of this tube is shown by the characteristic in Fig. 10. This characteristic is taken on a continuous potential circuit. It is rising throughout the working range, although nearly flat, and not drooping as is that of the arc. It differs considerably from the dynamic characteristic. The curve for reverse voltage is shown in Fig. 11. Measured on continuous potential and at a voltage of 1500, the reverse current of the above tube is about 1.5 milliamperes. This completeness of rectification is also shown by the oscillogram of Fig. 12, which shows the current delivered to a resistance load with the tube operating on a 1000-volt a-c. circuit. Any of the usual rectifier circuits may, of course be used. Both halves of the a-c. wave may be rectified and the delivered d-c. potential smoothed out in the usual manner.

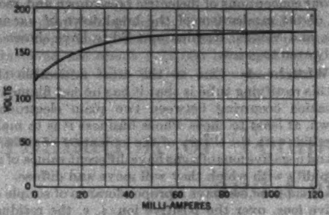

Fig. 10—Direct-Current Voltage Characteristic
Hollow electrode cathode

The tube noted above has a reasonable continuous overload capacity. Momentarily it can carry very much higher currents than normal. For a period of one second the tube may safely carry 10 amperes, or even more, and will rectify correctly under these conditions. Fig. 13 shows an oscillogram of current taken when the tube was thus handling a current of about this magnitude. Since the cooling of such a tube is largely by convection of the enclosed gas, the electrodes run normally much below a red heat, and the cooling is limited only by the facility with which the glass walls can dissipate to the surrounding air.

These tubes will operate in series and in parallel. In order to get very accurate sharing of current for parallel operation it is advisable to connect a small resistance in series with each tube. This is, however, not necessary if the tubes are correctly paired, for the characteristic is rising and parallel operation is accordingly stable. In series, no particular precautions are necessary. A high voltage will be equally shared between the tubes. It should be particularly noted in this connection that, when the tubes are used in series for the production of higher voltage, there is no problem of the insulation of filament batteries or other auxiliary devices. The tubes with their sockets as a whole are the only things that need to be insulated against full line potential.

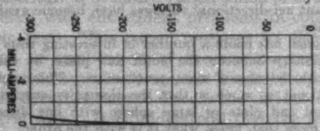

Fig. 11—Direct-Current Voltage Characteritics
Hollow electrode anode

When a tube of this model is operating, there is nothing that can be seen, except where a glow can be observed through a pinhole made in the cathode for this purpose. The heating of the bulb is the only indication that load is being carried.

The life of these tubes is very long. Tests made extending over several thousand hours on a number of models have not shown a change of 5 per cent in the characteristic at any time, and an examination of the electrodes at the end of such period has shown no measurable disintegration. It may be safely assumed for all ordinary purposes that the life is practically indefinite.

Fig. 12

These tubes do not have the instantaneous current limitation of the thermionic rectifier. Also the characteristic does not pass through the origin, as is there the case. There are many uses in which such a current limit or characteristic is necessary. The internal drop in the present models is inherently higher than in other types of rectifiers now in use on low-voltage circuits. As is usually the case with electrical apparatus, the rectifier field will always be shared by a number of widely different devices each particularly adapted for the use to which it is put. The particular portion of the field which will be occupied by the tube here described may be fairly accurately predicted from an examination of its inherent properties as presented in the paper above.

Fig. 13

VIII. Summary

Of the various types of non-metallic conduction, that employing electrons and gaseous ions is particularly noted. For practical purposes it has many advantages, such as the use of cold electrodes, comparatively unlimited current, and no inherent consumption of the working parts. In the past, however, this gaseous conduction has been little utilized commercially for it has been erratic and unreliable, and disintegration of electrodes and loss of working gas have accompanied it, with resulting short life.

A new engineering principle, the short path law, and closely connected ideas, have resulted in practically removing these disabilities. The discharge can now be made to occur where it is wanted, and controlled; so that devices employing gaseous conduction may be made consistent in behavior and reproduceable. By limiting the discharge entirely to electrodes which are constructed of certain favorable materials, disintegration has been made to disappear, and with it all trace of gaseous clean-up. The result is the possibility of constructing gaseous conduction devices which can be depended upon and which will last indefinitely.

Many applications of the principles may be made. Two of these, both rectifiers, illustrate the possibilities of the new arrangement. The first, described only briefly, obtains its control by the use of a magnetic field. The second obtains a similar control by the use of a space charge. The control is so complete that a ratio of currents in two directions of several thousand to one can readily be obtained. These rectifiers will readily stand a back voltage of several thousand. The current which they can pass is limited only by the question of getting rid of the heat evolved. The internal drop is around two hundred volts with the usual arrangements of the device. Heavy currents can be passed for short intervals.

One commercial model of this form of *S*-tube is rated at 50 milliamperes continuously, and 1500 volts back voltage. It has a substantial continuous overload capacity. It is designed primarily for charging fire alarm batteries and for the use of radio amateurs. For convenience, it is built to be screwed into the ordinary standard lamp socket. No other appurtenances or auxiliaries are necessary. The life is very long. The efficiency depends upon the circuit, and is high when high voltages are rectified. Such tubes may be used in series or parallel to any desired extent in order to obtain a desired voltage, current, or output.

Discussion

C. P. Steinmetz: This paper is interesting in the deductions you draw from it, because the statement made that a short gas path will not carry a discharge at voltages which will go over a much longer gas path, is rather in contradiction of our present ideas of the nature of breakdown in gases as determined by constant breakdown gradient.

This paper thus throws some doubt on our present explanations of disruptive phenomena in gases as determined by a constant breakdown gradient and energy distance.

I understand that the author had a pressure of three millimeters of mercury, that is about 1/250 atmosphere. This, reduced to the atmospheric pressure by proportionality, gives a very short gap and such a gap should hold a high voltage.

The whole subject is rather interesting theoretically from our present conception of the nature of breakdown of gases, and the matter is worthy of further investigation, since it is rather in line with many data and much information which has been accumulated in the last few years, which throws some doubt on many of our conceptions of dielectric breakdown and reopens the question of the mechanism of the breakdown of our insulating materials, and Messrs. Hayden and Eddy have shown that this may apply even to gases.

J. B. Whitehead: One of the most noticeable characteristics of this rectifying tube is that it has no hot filament, simply a rectification occurring between two plain electrodes. It is well known, at least to those whose business it is to make themselves familiar with the theory of the ionization of gases, that the positive and negative ions of a gas have different values of mobility, or the rapidity with which they will move and diffuse. At these pressures, I suppose, we have a preponderance of simple electrons or negative ions, over the positive ion, *i. e.* the residual of the molecule after it loses a negative ion.

Of course, these two types of ions have widely different values of mobility, consequently it does not appear that we have here the ordinary phenomenon of the breakdown of gases as discussed by Dr. Steinmetz, but that we have the simple generation of ions, by the natural process of ionization, and that the uni-directional conductivity of the tube, results from the difference in the mobility of the two types of ion; in other words, in sustained action, the lighter negative electrons are drained away, leaving the excess of positive ions, and the presence of that excess of positive ions must necessarily result in a uni-directional conductivity.

J. E. Shrader: The experiment described by Messrs. Bush and Smith is the noted experiment described by J. J. Thomson where the electric discharge at diminished pressures takes place through a long path rather than the alternative shorter path. The principle involved is that of ionization by collision. To acquire sufficient velocity to produce other ions by collision the path should be sufficiently long before impact—with gas molecules. When this velocity is sufficiently great more ions are formed by collision with the gas molecules and these ions so formed may acquire sufficiently high velocity to produce other ions.

Messrs Bush and Smith have here well utilized the phenomenon of ionization by collision.

C. P. Steinmetz: I might answer one point Dr. Whitehead brought up. I do not see why the mechanism of breakdown of several cm. gap length at atmospheric pressure should be any different from that of minute gaps with higher vacuum.

As regards the uni-directional feature of the conductivity that exists in long air gaps, this was first investigated by Mr. Peek with different electrodes, but it is only in the last year that high and constant uni-directional voltages have become available for investigation.

Mr. Hayden has made a number of interesting tests showing the conductivity between the point and plate, at voltages of 100,000, with distances of many centimeters. This conductivity is undirectional, so much so that the disruptive strength of the needle point and plate or large sphere with one direction of voltage is more than twice what it is with the other. This can be used to rectify alternating voltages and we are using such a plate and needle point gap with large condenser to produce high uni-directional voltages.

So it seems we get phenomena at these high voltages and large gaps similar to those we are known to get in minute gaps at high vacuua.

V. Bush: The experiment of the long and short paths, which I believe was due to Hittorf, shows that in general the discharge prefers a long path to a short one, when the short path is short under the definition of the paper, and the long path is not purposely suppressed. The point I want to emphasize is the extent of this preference, which has not been generally realized. The preference may readily be so strong that, if the long path is suppressed, the short path will not break down at, say, 10,000 volts, whereas, the long path would if allowed break down at 300 volts.

As to another point, brought up by Dr. Whitehead: Of course, if we attempt to apply this principle at atmospheric pressures, the distances involved are about 1/10,000 of a centimeter as Dr. Steinmetz points out. With the low pressures, we have to deal almost entirely with positive ions and electrons, whereas at the higher pressures, the effect of the negative ions is ordinarily also important. It is not at all settled that this would still be true with very close separations.

There is one further point. I would like to distinguish this apparatus from the rectifier which depends simply on dissymmetry of electrodes, and which thus depends for its action on the difference in breakdown voltage in the two directions,—such as the point and plate and the corona rectifier. In the non magnetic type of this tube the breakdown voltage in the two directions is approximately the same, but the characteristics in the two directions are very widely different.

Determination of Temperature of Electrical Apparatus and Cables in Service

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Temperature measurements constitute a large part of the work of the test department of an electric light and power company in the acceptance and maintenance of the electrical equipment. The methods of measuring temperature which are applicable to this work are discussed in this article. The characteristics of the different kinds of temperature measuring apparatus are brought out by describing a number of actual tests.

In the article considerable attention has been given to various forms of thermocouples which have been found very useful in obtaining temperature measurements on cables and in underground conduit systems.

THE following paper is intended as a discussion of the various commonly used methods of determining temperature, such as would be employed in the test department of an electric light and power company. The temperature measurements, as a matter of fact, constitute a large part of the acceptance tests of electrical equipment and supplies, and form a considerable part of the investigation of service performance and characteristics after the equipment has been accepted and placed in service.

The four commonly used means of measuring temperature are by thermometer, by resistance thermometer, by thermocouple and by change in resistance in the winding or circuits of the apparatus under test.

If an electric light and power company rigorously maintains the policy of testing for acceptance, as far as possible, equipment and materials purchased, it results in the presentation of many varied kinds of equipment and material with consequent problems in connection with their test. This paper proposes to discuss the adaptation or application of the various methods of measuring temperature to specific kinds of equipment and material, rather than to discuss the various methods in a general way. It is understood that the temperature measuring devices themselves are well established and are not presented here as novel and probably not new in their application. However, many test details arise in connection with the use or application of the various forms of measurement to the particular equipment under test. The discussion of a number of specific test conditions will bring out some of the characteristics and limitations of the various methods of measuring temperature.

The work of a test department of this character covers a fairly broad field, but it does not require the use of every type of temperature measuring apparatus, nor are all types suited for the conditions encountered. In general, the temperatures which are measured are less than 200 deg. cent. and in most cases are confined within the limits permissible in electrical apparatus. The measurements usually need not be made more precisely than to the nearest degree centigrade. Accordingly, the discussion which follows will pertain to measurements in this temperature range and of this general precision.

Before describing the detailed applications, some of the types and characteristics of the four kinds of temperature measuring apparatus will be briefly discussed.

The thermometer method is the simplest and most convenient to use. With the thermometer the indication of temperature is obtained directly without the use of any auxiliary equipment.

The following forms of thermometers are found to supply the general demands of test work.

1. Indicating (mercury and spirit).
2. Recording.
3. Maximum and minimum indicating (constricted-bore type and Six's type).

The mercury indicating thermometers of the gas filled type are to be preferred for most work. These thermometers are calibrated for partial immersion

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(frequently 3 inches). This is desirable as in ordinary use only the bulb is in contact with the apparatus. The spirit thermometers are calibrated for full immersion and are used in locations where air or fluid temperatures are desired and danger from high voltage makes it inexpedient to use mercury thermometers. In case of breakage of spirit thermometers, the hazard from voltage breakdown in high tension apparatus is less than with mercury thermometers, due to the quick evaporation of the fluid.

The recording thermometers are standard instruments which can be purchased in various types and ranges. It is found that the self-contained instrument suited for ambient air temperature measurements has the widest application for portable use.

Where apparatus is inaccessible or where there is hazard from high voltage, it is frequently not practicable to use thermometers. In such cases, the resistance thermometer or thermocouple properly insulated or the change in resistance method are used.

The shape and bulk of the resistance thermometer units do not always make them readily applicable to test conditions. In order to obtain sufficient strength, the unit must be made large, the small units being fragile and expensive. This type of apparatus has been found better suited for permanent installation rather than for portable testing work.

In general test work, the thermocouple has proved more useful than the resistance thermometer. It is small, strong, easily made up, and will give readings at a distance with a sufficient degree of accuracy. A copper constantan couple is used for temperatures up to 200 deg. cent. The indication is obtained by means of a potentiometer type temperature indicator calibrated directly in degrees for this type of couple. This is a null method of measurement which avoids correction for lengths of connecting leads and permits accurate determination of temperatures at considerable distance from the instrument.

The thermocouple wire for use with these instruments can be purchased with a guarantee that the results will be correct within one degree centigrade over the entire scale. This is sufficiently accurate for the work encountered, and presupposes that the constantan wire has been carefully selected. The two conductors are made up in a duplex wire and each insulated with rubber. Surrounding both wires there is a weatherproof covering. Rubber insulation should cover each wire separately as cotton insulation alone is liable to absorb moisture and produce internal galvanic action introducing errors in the temperature readings.

It has been found desirable to give each shipment of thermocouple wire on receipt acceptance tests to insure that its characteristics are as guaranteed and to insure against defective insulation.

1. Each coil of wire is tested as a thermocouple between 20 deg. cent. and 150 deg. cent. with the portable direct reading potentiometer temperature indicators, in order to ascertain that its e. m. f. agrees with the standard curve.

2. The insulation resistance between the two conductors of each coil is measured with a 1000-volt megger.

3. A 50-foot sample is cut from the coil and its insulation resistance is measured as in (2).

4. The sample in (3) is heated to 100 deg. cent. for one hour and then connected to a temperature indicator with the end open circuited in order to determine whether any electrochemical e. m. f. is generated.

5. The insulation resistance of the sample is measured while hot, following the same precedure as in (3).

After passing these tests, the wire is ready for use. Couples can be made up in the field by simply twisting the copper and constantan together and soldering the junction. The length can be made to suit the field con-conditions, and no further calibration is needed.

Fig. 1

The fourth method of measuring temperatures makes use of the change in resistance of the windings. The results obtained by this method are accepted as the average temperature of the conductors. It is not possible to measure hot spot temperatures by this method. In tests on transformers, regulators, reactors and cables, the resistance method is extensively used.

With the above methods available, the selection of the method depends on the character and the location of the apparatus to be tested. Some of the typical tests are described below, and also the reason for selecting the various methods discussed. In describing the tests only brief mention is made of the technical details except as they affect the methods of measuring temperatures. In order to give a clearer idea of the equipment under test and the temperature measuring apparatus, illustrations and diagrams of many of the tests have been included.

In Fig. 1, a group of circuit breakers is shown set up for test. The thermometer method was used because the apparatus was easily accessible and this method was the simplest. The thermometers were placed at the points where the highest temperatures were expected, at the contacts and joints. The bulbs were placed in contact with these parts and were covered with putty. On account of the small size of the breakers, the area covered by the thermometers and putty was kept to a minimum so that the radiating properties were not appreciably altered. The thickness of the putty covering was sufficient to protect the bulb from the influence of the air.

FIG. 2

In tests where the radiating surface is very small, thermocouples have the advantage over thermometers. The arrangements for such a test are shown in Fig. 2, which is an illustration of small copper catches set up for test. The thermocouples were soldered to the catch, bus and lug. If thermometers had been used, the bulb and putty would have seriously reduced the radiating surface. The thermocouple junctions and the spot of solder did not appreciably alter the radiation, so that it was possible to make a detailed temperature survey with very little change in normal operating conditions.

FIG. 3

In some cases, a number of methods find application. Fig. 3 is an illustration of the cable and equipment. In Fig. 4 a diagrammatic layout of the cables is given which shows the location of the thermometers and thermocouples. The cable was a three-conductor cambric-insulated high-voltage cable. Over the outer belt of insulation, there is a steel armor and over this, a weatherproof covering. The surfaces of the cables were painted so as to give different radiating effects.

The conductors of the various sections were connected together so that current from a low-voltage supply could be circulated through each of the phases. The rated potential difference was maintained by another source, so that the net dielectric losses were the same as in normal service. In arranging the circuits, provision was made so that by using a switch to throw from a-c. to d-c. supply, the conductor resistance could be measured immediately after opening the test current. The leads for the voltage measurements were permanently soldered to the conductors and brought to a central point so that the readings could be quickly taken and sources of error due to poor connections avoided. From these measurements, the average temperature of the conductors in each section was determined.

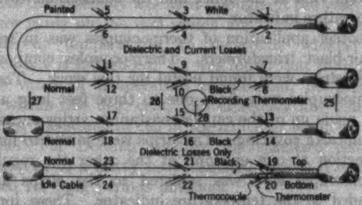

FIG. 4—AERIAL CABLE TEST
Location of thermometers and thermocouples.

The temperature of the steel armor was measured by means of thermocouples inserted under the armor through slits in the weatherproof covering. The thermocouple wires were brought back to a dial switch shown at the center of Fig. 3. The temperature indicator was placed on an insulated platform on which the observer also sat when taking readings. This safeguard was necessary as the thermocouple leads might become alive due to a failure in the insulation.

On the surface of the cables, thermometers were used to obtain the temperature. These thermometers were held down with putty. The air temperatures were measured by means of both indicating and recording thermometers.

When it is desired to obtain maximum internal temperatures, such as in a splice, the thermocouple is the best method. The location of the probable hot spots is determined and the thermocouples are located at these points.

For example, a test was made on a splice of a concentric one million-cir. mil, lead-covered cable. The problem was to analyze the temperatures in and around the splice after it was completed as it would be made up in service. The thermocouples were therefore built into the splice as it progressed and the normal lay of the cable insulation and lead armor was disturbed as little as possible. One thermocouple was placed at the joint in the inner conductor. This was fastened to the wiping solder used at that point. Other thermocouples were spot-soldered to the inner conductor about four inches each side of the joint, and the leads brought through a small triangular slot cut in the paper insulation, the cut being so made that the insulation could be bent back in place after the thermocouple was located. A cross section of the splice is shown in Fig. 5 and the location of the thermocouples on the inner and outer conductors and sheath are indicated.

The leads to the thermocouples were made as small as possible so that they could be all grouped together and brought out through a hole in the lead sleeve of the splice which was securely sealed. Fig. 6 shows an external view of the splice and the connections to the temperature indicator.

Another application of thermocouples was in tests on air-blast transformers. Thermocouples composed of flat strips were found useful for this work. These thermocouples were from one to three feet long and were made up of the copper-constantan strips encased in a micarta covering. The strips were joined to form a junction at one end and at the other the regular thermocouple wire was soldered to the strips and extended to the temperature indicator. These junctions were wedged between the low-tension winding and the separators.

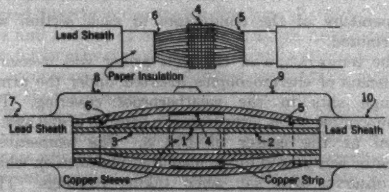

Fig. 5

Such thermocouples could not be placed in contact with the high-tension windings with safety. In order to measure the temperature of the high-tension windings, thermometers were used. These were fastened on the coils usually at the top. The readings of the thermometers were obtained through the top of the transformer by protecting the eyes with goggles, (on account of the air blast). If the thermometers were located at greater distances than two feet a galvanometer telescope was used. In addition, thermometers were lowered on strings in the air passages in order to obtain the air temperature. Spirit thermometers were used for this purpose as they were less liable to cause a ground if broken inside of the transformers.

On rotating machinery, the temperatures are obtained by thermometers when the apparatus is accessible. For example, on synchronous converters, and generators and motors, the thermometers are placed on the stationary parts such as the field coils, pole tips, frame, bearings and brush brackets and collector buses. On induction motors and other apparatus on which the major part of the windings are imbedded the resistance method gives the best results. However, thermometers are always used if possible to supplement this method.

Fig. 6

The temperature measurements of the rotating parts are made after the machine has come to rest at which time thermometers are quickly placed on the commutator slip rings and armature windings. These readings are taken at intervals of a minute or less until the temperature has started to decrease.

On the larger higher-speed, high-voltage equipment such as turbo alternators, the temperature measurements are made by means of imbedded thermocouples or resistance thermometers usually placed by the manufacturer. The temperatures of the stationary parts, if accessible, are measured by thermometers, or thermocouples.

For investigating temperature conditions in the various parts of an underground transmission and distributing system, the thermocouple was found to be very convenient and adaptable. Tests made on cables in manholes, sheath temperature and manhole air conditions were made with thermocouple and recording thermometers. On low-tension cables, the thermocouple junctions were soldered directly to the sheath. On high-voltage cables, the junctions of the thermocouple wire were preferably soldered to small pieces of sheet copper about ½ in. by 1 in., and these securely held in contact with the sheath of the cable by means of small wooden blocks of about the same area.

The piece of sheet copper increased the contact area of the junction, thus insuring that the thermocouple junction assumed as nearly as possible the temperature of the sheath. The thermocouple junction alone produced a very small contact. Due to this relatively small volume compared to the size of its own connecting leads, the leads may conduct the heat away if they are of a lower temperature than the thermocouple in contact with the cable, which is usually the case. Such a condition would result in a lower indication of temperature than actually existed on the sheath of the cable.

The foregoing point is of general application and it has been found necessary to analyze the above effect from various angles. As a result, the junctions of the thermocouple wire were fitted in special copper slugs which have been developed by the test department of the New York Edison Company. This slug is shown in the insert in Fig. 7. This form was designed primarily for measurements of duct temperatures which by nature do not change rapidly. It is about two inches long and ⅜ of an inch in diameter, with grooves cut parallel to the axis so as to give a larger exposed area. The slug increased the exposed surface of the couple and eliminates any error which may be due to the leads conducting heat away from the couple. The increased mass of the couple made the measurements of air temperature more reliable, in that the couple did not show temperature changes with each slight draft of air. The time lag introduced by the increased mass was less than one half hour and was considered satisfactory for duct temperature measurements. Obviously this time constant may be increased or diminished by varying the mass and relative radiating surface of the terminal.

Fig. 7

Extensive underground temperature surveys have been made in duct banks by means of gang-cables of thermocouples, approximately 350 feet long. The entire gang-cables are built up beginning with a ⅜-in. steel-wire rope to which the thermocouples are attached. The thermocouples fitted with the above mentioned slugs are spaced every 30 feet and the pair of leads to each one brought back to one end of the cable. All the leads are bound with cord about every foot. Four layers of tape are wrapped over the entire length to protect the cable from abrasion and slight moisture.

In attaching these junctions on the cable, the copper slugs are heat insulated from the steel rope by means of a number of layers of tape. In order to make certain that the slugs do not come in contact with the duct walls, knobs were built up on the cable each side of the slug as shown in Fig. 6.

The complete equipment used with the cable is shown in Fig. 7. The thermocouple wires were brought back to a dial selector switch which permits any couple to be connected to the temperature indicator.

As this assembly was used throughout the year, tests were made on the dial switch and indicator when at different temperatures to determine whether the accuracy is influenced. It was found that throughout the range of temperature encountered, the precision is within one deg. cent. At extremely low temperatures, the standard cell in the indicator became unreliable. For freezing weather the standard cell was removed to a heavy heat insulated case so it could be used for long periods outdoors.

Based on the experience accumulated in using thermocouples and the gang cables, it is felt that the general accuracy of temperature measurement which should be obtained is within one degree centigrade. It will be appreciated that with a new application of temperature measuring apparatus such as the gang cable, a certain number of practical difficulties may be encountered in the field. This has been the case in this instance and several sources of error have been encountered and eliminated which are recorded here for the benefit of others who may desire to attempt similar investigations:

1. Thermocouple wire made by a reputable manufacturer was used at first which had unimpregnated cotton insulation between the conductors. It was found that this wire readily absorbed moisture of various and unknown chemical characteristics, which produced galvanic effects and caused errors in the temperature readings. Immediately this condition was understood, it was corrected by using rubber insulation around each individual conductor, and also around the pair of conductors comprising the thermocouple.

2. After the gang cables had been in service for a considerable period, it was found that breakages occurred in the copper conductor near the copper

slug terminal. Relatively few breakages occurred in the constantan wire. These breakages were due to the wear and tear in service incidental to pulling the cable in and out of ducts. It was exceedingly difficult to detect the breakage of the wire since mud and moisture from the duct entered the cable and produced galvanic action between the conductors at the break near the slug terminal. This error has been eliminated by substituting a stranded copper conductor for the solid copper conductor. Additional protection has been obtained by water-proofing the junction between the thermocouple insulation and the copper slug terminal to exclude moisture from the thermocouple wire.

3. It was found that the insulation ordinarily furnished with the thermocouple wire did not satisfactorily resist service usage. Accordingly, thermocouple wire was obtained insulated with especially durable insulation capable of standing considerably more wear and tear than the ordinary rubber insulation previously furnished.

This thermocouple gang-cable has been found very useful in plotting the temperatures along a duct bank. For analyzing temperatures which might emanate internally in the cables lying in the bank or externally from steam pipes and other sources of heat outside the bank. This gang cable is of such size that it can be used only where an empty duct is available in the bank, as it cannot be pulled through a duct already occupied by a cable.

In the morning the cable was pulled into an empty duct of a bank so that the first thermocouple extended into the next manhole. The manholes were closed and readings taken over the peak load period, after which time the cable was removed.

As a check on the accuracy of the thermocouple indications, and in order to prevent any discrepancies from entering, a thermometer was placed in contact with the terminal of the first thermocouple in the far manhole. Simultaneous readings were taken on the thermometer and thermocouple just before removal.

The life of a cable of this character in nearly continuous testing service at numerous locations is about three months.

In cases where the space was limited, or it was inconvenient to bring out thermocouple leads, the maximum indicating thermometer was used. There are the two types, namely the Six's maximum and minimum indicating and the restricted bore mercury thermometer which is only maximum indicating. These were placed in junction boxes in the middle of streets, where, due to traffic, thermocouples could not be used and where on account of the restricted space, it was impossible to set recording thermometers. The results obtained by these thermometers gave only the range of temperature during a load cycle.

The data and methods given above are intended to set forth some of the procedure being used to measure temperatures in the general testing work of a large public utility. They are advanced with the belief that they will be of value to engineers engaged in similar work and will bring out discussions of other methods for achieving the necessary test results.

Discussion

E. S. Lee: Those of us who are engaged in making temperature measurements know that heat is elusive and gets away from us very easily, and we have to take due consideration of the fact that it may go from one place to another by conduction or by convection or by radiation; the measurement of temperature is therefore complex.

As Mr. Rutan said, the thermometer method is simple and convenient. We make such extensive use of the mercury thermometer in our daily life that we sometimes apply it in our engineering without knowledge of the fact that errors may exist. Differences in temperature along the thermometer stem, poor contact of the bulb with the measuring surface, broken mercury column are the most frequent sources of error. Formulas are available for emergent stem correction; their use is not always productive of accurate results. Contact errors can be eliminated if care and thought are used. Felt pads and putty both provide means for affixing thermometers. Broken mercury columns can be detected by careful inspection.

If you want to find out something concerning the accuracy of the results that you are getting from any measurement with mercury thermometers, just make a measurement and remove the thermometer completely; replace it and take another observation. Do this half a dozen times and you may find there is considerable deviation. There may be a deviation of as much as 5 degrees, even when you are trying to keep everything else constant, and you must be careful to do that.

Mr. Rutan speaks of the resistance thermometer, and, in his particular case he has not made so very much use of it. Use can be made of it in a great many installations and it is particularly convenient in that you can read the indicator directly without having to make any manipulations, the exciting voltage remaining constant. For tests where facility of reading the indication is an important factor, the resistance thermometer should be considered.

In regard to the thermocouple, what Mr. Rutan has said about its being of wide application, is very true. In connection with his acceptance tests, in order to assure himself that the wire is according to the specification, I find that he speaks of testing it up to 150 deg. cent., and that he heats it up to 100 deg. cent. for an hour to see that there are no parasitic currents generated to affect the result. I am wondering if Mr. Rutan uses rubber thermocouples at such temperatures as 100 or 150, or 200 deg. cent.? If rubber is used at these temperatures, I think you will get into trouble. If you are using a thermocouple junction which will stand these high temperatures, with rubber and cotton covered leads out in the regions where the temperatures are low, you may be all right. Leads covered with rubber only are positively detrimental.

In item 4, on page 465, I understand from what Mr. Rutan says that he takes a 50-ft. sample, winds it up, and puts it in the oven a 100 deg. cent., allowing one end to extend into the open to which an indicator is connected. I would suggest another test whereby the entire length of thermocouple is extended in the room, the ends of this thermocouple being adjacent, one being connected to an indicator. Now heat the thermocouple to any desired temperature at different points along its length. The indicator should give zero deflection if the thermocouple materials and insulation are without defect.

E. J. Rutan: Replying to Mr. Lee in regard to the use of rubber insulated thermocouple wire at 100 deg. cent. or above I wish to state that the temperature limits given were mentioned in connection with the junction temperature. The wire itself is usually in air at a much lower temperature. In cases where the wires may pass through high temperature spaces leads insulated with glass or vitreous beads are used in place of the rubber insulation.

Mr. Lee also suggested heating the wire under test at different points along the length in order to detect defects in the insulation. This method had been tried but was more time-consuming than the method outlined in the paper which gives the desired information on a full length with one test.

The Economics of Direct-Current Railway Distribution

With Particular Reference to the Automatic Substation

BY LAWRENCE P. CRECELIUS
Member, A. I. E. E.
and
VICTOR B. PHILLIPS
Consulting Engineers, Cleveland, O.

Review of the Subject.*—The comparatively recent development of the full automatic substation and also the automatic substation combined with remote control, has served to re-open the entire subject of the economics of distribution. But quite aside from the questions that the automatic substation has presented, the great fluctuations in the prices of materials and of labor have made necessary renewed study of this subject. In other words, the proper design of a distribution system should represent a balance between all of the different items of cost that go to make up the total cost of power. Any change in the relative cost of materials as against labor or of a certain class of materials as against another class of materials tends to upset such a balance. Now that we begin to emerge from the unsettled conditions of the past few years during which the old relationships have been substantially changed, it is necessary to ask the question whether or not the rules by which distribution systems have been planned in the past still apply.*

More specifically, it is the purpose of this paper to determine, first, the relations that govern the size of feeders and the correct feeder layouts for any given arrangement of substations, and second, the principles underlying the correct location, size, and type of substations, assuming the fullest development of automatic and semi-automatic control.

There is involved also the important question of stray currents. Regardless of the merits of the electrolysis controversy, the minimizing of stray currents is certainly to be desired by the electric railways. The most effective method of accomplishing this is increasing the number of distributing points. If a large number of distributing points be justified from an economic standpoint, and if furthermore this be found practicable from an operating standpoint, then the problem of electrolysis may perhaps cease to exist. Thus the inquiry is doubly pertinent.

The cost of distribution in large cities of the size of Cleveland, Detroit, or St. Louis, comprising the carrying charges on the feeder, the heating losses in the feeders and the carrying charges on the equipment necessary to supply these losses, is considerably in excess of $200,000 per year. It is apparent that a careful study of this item of cost will more than likely be justified by the savings that will result.

There are not at the present time sufficient accurate data on cost and performance of automatic substations to make possible a precise analysis of specific cases. In lieu of this it is the authors' purpose to show limiting conditions and by example to illustrate the relation of the various determining factors to the final cost.

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1. Feeder Circuits

THE total cost of feeder distribution comprises the following:

(1) Carrying charges on feeder investment.

(2) Carrying charges on (a) generating plant, (b) transmission lines, and (c) substations, for that part of the investment that supplies the losses in the feeders.

(3) Operating expenses of the generating plant, transmission lines and substations for that energy which is lost through heating of the feeders.

In cities of about the size of Cleveland the following conditions are fairly representative:

(1)	Feeder investment, $1,000,000. Carrying charges @ 13 per cent per annum	$130,000
(2)	Generating plant, transmission lines and substation investment per kw. (d-c.) demand, $165. At 14 per cent per annum these carrying charges are $23 per kw. Maximum demand, 40,000 kw. Distribution loss during peak, 10 per cent. Carrying charges, 0.10 × 40,000 × $23	92,000
(3)	Operating expenses of generating plant, transmission lines and substations. 0.8 cent per kw-hr. At 25 per cent loss factor the average system loss will be 1,000 kw. or 8,760,000 kw-hrs. per year	70,000
	Total	$292,000

Presented at the Annual Convention of the A. I. E. E., Niagara, Falls, Ont., June 26-30, 1922.

It is readily apparent that an increase in the copper investment will serve to cut down the heating losses and consequently those items of cost that depend on these losses. There must be, therefore, a proper size for every feeder representing an economic balance between the copper carrying charges on the one hand and the copper losses on the other, for which size the total cost is a minimum.

Three distinct types of feeders will be considered:

(a) Uniform cross-section, entire load concentrated at the end.

(b) Uniform cross-section, load uniformly distributed along feeder down to zero at end or neutral point.

(c) Uniformly tapering cross-section, load uniformly distributed along feeder down to zero at end or neutral point. This type of feeder is of course purely theoretical. It may, however, be considered as representing the limiting condition that is approached by stepping down the feeder size.

The items of cost set forth above will be expressed by the following symbols:

LIST OF SYMBOLS

C_F—Total annual cost of feeder circuit (dollars).

C_g— " " " " rail and ground circuit (dollars).

C — " " " " entire distribution circuit (dollars).

D —Distance to end of feeder or neutral point (feet). In the case of variable distributing distances D is the distance corresponding to peak load.

E —Voltage drop to end of feeder or to neutral point for maximum (peak) current.

E_F—Voltage drop to end of feeder or to neutral point for maximum (peak) current, in feeder only.

e —Operating expenses for generating plant, transmission lines and substation (dollars per d-c. kilowatt-hour).

f —Carrying charges on feeder in place (dollars per lb.).

G —Effective resistance of rail and ground circuit (ohms per ft.).

I —Maximum (peak) current in feeder at substation end (amperes), *e. g.* average of 15-minute peak or other basis for determining proper installed capacity.

L —Loss factor, average of the squares of the momentary feeder currents divided by the maximum current (I) squared.

m —Cross-section of feeder at substation end (circular mils).

p —Carrying charges (interest, depreciation and taxes) on generating plant, transmission lines, and substations (dollars per d-c. kw. demand per year).

The following equations in sections 1-3 (inclusive) are derived for the condition that distributing distances remain the same for all loads. The effect of varying distributing distances with load will be considered in section 4.

Type (a) feeder, uniform cross-section, concentrated load.

$$C_F = 3.67 \times 10^{-6}\, m\, D\, f + 0.001 \times I^2\, p\, D \left(\frac{10.35}{m}\right) + 8.76 \times I^2\, L\, e\, D \left(\frac{10.35}{m}\right) \qquad (1)$$

The factor 3.67 is pounds per foot per 1,000,000-cir. mil cable with triple braid weatherproof insulation, the factor is slightly greater, for smaller sizes of cable.

The first problem is to express m in terms of the constants D, e, f, I, L and p for the minimum cost (C_F), according to Kelvin's law of economy, *i. e.*,

$$m = I \sqrt{\frac{2820\, p + 24.7 \times 10^6\, L\, e}{f}}$$

$$C_F \text{ (minimum)} = 0.000390\, I\, D \sqrt{f\,(p + 8760\, L\, e)}$$

$$E_F = I \left(\frac{10.35}{m}\right)$$

EXAMPLE:

Let D = 1.5 miles or 7920 feet
e = \$0.008 per kw-hr.

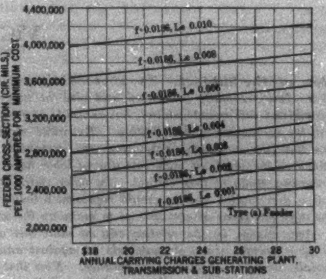

FIG. 1

f = 0.022 Multiply section by 0.9195
f = 0.025 Multiply section by 0.8626
f = 0.028 Multiply section by 0.8154
For type (*b*) feeder multiply section by 0.577
For type (c) feeder multiply section by 1.000
For 1,000,000-cir. mil, T. B. W. P. feeder multiply section by 1.000
For 500,000-cir. mil, T. B. W. P. feeder multiply section by 0.985
For 4/0 T. B. W. P. feeder multiply section by 0.985
For 2/0 T. B. W. P. feeder multiply section by 0.962
For bare feeder, all sizes, multiply section by 1.090

f = \$0.0186 = 12 per cent on feeder at \$0.155 per lb.
I = 750 amperes
L = 0.25 (For Cleveland Rwy. Co., load factor approximately 40 per cent)
p = \$23.00.

Then m = 1,860,000 circular mils.
C_F (min.) = \$2010 per annum.
E_F = 33 volts.

Type (b) feeder, uniform section and distributed load.

In this type of feeder, the above equations become (see Appendix I):

$$m = 0.577\, I \sqrt{\frac{2820\, p + 24.7 \times 10^6\, L\, e}{f}}$$

$$C_F \text{ (min.)} = 0.000225\, I\, D \sqrt{f\,(p + 8760\, L\, e)}$$

$$E_F = I/2 \left(\frac{10.35\, D}{m}\right)$$

$$\left.\begin{matrix} m \\ C_r \text{ (min.)} \\ E_r \end{matrix}\right(\text{for type (b)} \quad \left.\begin{matrix} 0.577 \times m \\ = 0.577 \times C_r \text{ (min.)} \\ 0.866 \times E_r \end{matrix}\right) \text{for type (a)}$$

Example: Using the same values for D, e, f, I, L and p as in the example for type (a)

$m = 1{,}075{,}000$ circular mils.

C_r (min.) = \$1160 per annum.

$E_r = 28.6$ volts.

Type (c) feeder, tapering section and distributed load. The feeder may be considered as the summation of small increments each of which is the same as type (a) feeder, so that losses and amount of copper are one-half what they are for type (a). (see Appendix II.)

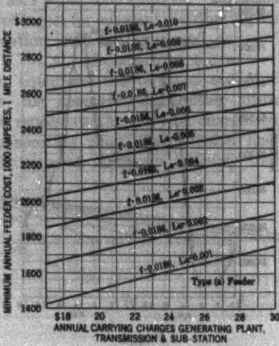

Fig. 2

$f = 0.022$ Multiply cost by 1.0875
$f = 0.025$ Multiply cost by 1.1593
$f = 0.028$ Multiply cost by 1.2264
For type (b) feeder multiply cost by 0.577
For type (c) feeder multiply cost by 0.500
For 1,000,000-cir. mil, T. B. W. P. feeder multiply cost by 1.000
For 500,000-cir. mil, T. B. W. P. feeder multiply cost by 1.015
For 4/0 T. B. W. P. feeder multiply cost by 1.015
For 2/0 T. B. W. P. feeder multiply cost by 1.039
For bare feeder, all sizes, multiply cost by 0.917

$$m = I \sqrt{\frac{2820\,p + 24.7 \times 10^6\,L\,e}{f}}$$

(same as for type (a))

$$C_r \text{ (min.)} = 0.000195\,I\,D\,\sqrt{f\,(p + 8760\,L\,e)}$$

$$E_r = I\,\frac{(10.35\,D)}{m} \quad \text{(same as for type (a))}$$

Example: Using same values for D, e, f, I, L and p as in examples for types (a) and (b)

$m = 1{,}860{,}000$ circular mils.

C_r (min.) = \$1005 per annum.

$E_r = 33$ volts.

2. Rail and Ground Circuits.

These circuits are not susceptible of precise determination principally on account of variation in joint resistance and leakage to ground. Were it not for these two factors it would be possible to calculate return circuit resistances and drops with a fair degree of accuracy. Fortunately, good practise is making this problem easier. The Report of the American Committee on Electrolysis in the "Summary of Good Practise" calls for (1) track construction and bonding that will cut down resistance to a minimum, with such cross-bonding as will serve to minimize the effect of joint failures, and (2) track insulation insofar as this is not inconsistent with other considerations. There are large differences in the resistances to ground of the several different types of roadbed construction now in vogue. Good practise, however, tends toward the roadbeds of higher resistance and the consequent reduction of stray currents.

The above report condemns the "reinforcement of rail conductivity" either by parallel copper, because this copper cannot be economically loaded, or by buried conductors which "increase the contact area between return circuit and the earth." It points out the high cost of insulated negative feeders. All of these recommendations make for the simplification of the problem which is being considered here.

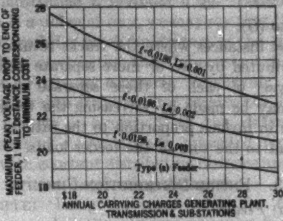

Fig. 3

$f = 0.022$ Multiply drop by 1.0875
$f = 0.025$ Multiply drop by 1.1593
$f = 0.028$ Multiply drop by 1.2264
For type (b) feeder multiply drop by 0.866
For type (c) feeder multiply drop by 1.000
For 1,000,000-cir. mil, T. B. W. P. feeder multiply drop by 1.000
For 500,000-cir. mil, T. B. W. P. feeder multiply drop by 1.015
For 4/0 T. B. W. P. feeder multiply drop by 1.015
For 2/0 T. B. W. P. feeder multiply drop by 1.039
For bare feeder, all sizes, multiply drop by 0.917

As the number of distributing points is increased, track drops decrease very rapidly, theoretically as the square of the distance. It is therefore apparent that decreased distributing distances will serve both to cut down stray currents and make possible the more exact determination of return circuit resistances.

For the purpose of an economic analysis the effective resistance of the rail and ground circuit in most cases may be based upon the rail resistance, without any great error. On a properly maintained city system, current returned through other paths than the rails should not exceed 25 per cent. This is at least a rough measure of the maximum error that might result from using rail resistance as the basis for return circuit resistance. If, however, leakage is known to be approximately 25 per cent in the case of a certain line and proper correction is made for this in estimating return circuit resistance, the error should be quite small so as to be practically a negligible part of the total distribution circuit resistance.

If bonded joints are regularly tested and bad joints repaired when found, it is possible to reduce the number of joints having an equivalent resistance of less than 9 ft. of rail to 5 per cent or less of all joints. If the percentage of such bad joints be known, it becomes possible to determine the rail circuit resistance quite accurately, especially if there be proper cross-bonding. Welded joints frequently have a resistance less than that of continuous rail so that the resistance of such track may generally be assumed to be the same as for continuous rail.

The distribution of current in the track circuit will of course be the same as in the feeder provided it returns only the current of that one feeder. It follows therefore that the the second and third terms of equation (1) apply to the track circuit excepting that the resistance per ft. $\left(\frac{10.35}{m}\right.$ in the case of the feeder$\left.\right)$ will be changed to (G).

In those instances where the tracks return the current distributed by two or more separate feeders then the analysis of each of these separate distribution circuits may be made by increasing the track circuit resistance in inverse proportion to the ratio of the one feeder load to the sum of the feeder loads.

3. ENTIRE DISTRIBUTION CIRCUITS

Type (*a*) *Feeder.*

$$C = 3.67 \times 10^{-6}\, m\, D\, f + 0.001 \times I^2\, p\, D \left(\frac{10.35}{m} + G\right) + 8.76 \times I^2\, L\, e\, D \left(\frac{10.35}{m} + G\right) \qquad (2)$$

$$C\ (\text{min.}) = 0.000390\, I\, D \sqrt{f\, (p + 8760\, L\, e} + I^2\, D\, G\, (0.001\, p + 8.76\, L\, e)$$

$$E = I\, D \left(\frac{10.35}{m} + G\right)$$

The introduction of G into the equation does not change the value of m as previously expressed for the feeder circuit.

Type (*b*) *Feeder.*

$$C\ (\text{min.}) = 0.000225\, I\, D \sqrt{f\, (p + 8760\, L\, e} + \frac{I^2\, D\, G}{3}\, (0.001\, p + 8.76\, L\, e)$$

$$E = \frac{I\, D}{2} \left(\frac{10.35}{m} + G\right)$$

Type (*c*) *Feeder.*

$$C\ (\text{min.}) = 0.000195\, I\, D \sqrt{f\, (p + 8760\, L\, e)} + \frac{I^2\, D\, G}{3}\, (0.001\, p + 8.76\, L\, e)$$

$$E = I\, D\, \frac{(10.35)}{m} + \frac{I\, D\, G}{2}$$

4. DISTRIBUTION DISTANCES VARIABLE WITH VARIABLE LOAD[8]

All of the foregoing relations and equations have been based upon the assumption that the distributing distances are the same at all loads. Even with multiple-unit stations this will rarely be the case, since during light loads some stations must be shut down, in order to load the other stations up to a point of reasonable efficiency. In the case of single-unit substations in cities, it becomes necessary to follow the load by varying the number of substations in operation, and this results in larger distributing distances during periods of lighter loads. The effect of this method of operation on the above equations will be worked out by an illustration.

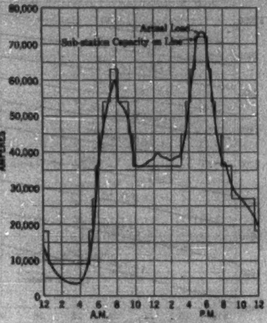

FIG. 4

The accompanying load curve (Fig. 4) shows the following of the load by putting on and taking off substation capacity. It should be possible with remote control and careful study of load conditions for the chief operator to follow the load quite closely and thus to keep all machines loaded to somewhere near rated capacity with the consequent high efficiency. It will be noted on the load curve that the substation capacity has been added in eight steps of 9000 amperes each. It will be assumed that each step represents an integral number of single-unit substations of uniform size and that the load on the different section of the systems varies about the same as the composite load curve. On a system of this kind with a large number of substations, it is necessary to use uniform section feeders between substations because of the shutting down of some substations during off-peak hours and the consequent necessity of feeding these substation areas from adjacent stations. Also on such a system the type (*a*) feeder would be used rarely if at all and the type (*c*) feeder would be used only in the outlying sections for the deadended feeders. It is therefore proper to assume that in the case of such a system as is being considered here, practically all feeders will be type (*b*) feeders (*i. e.* uniform section and uniformly distributed load).

Let D (constant) represent the distributing distance any one of substation when all substations are operating and I the proportional part of the substation rated capacity that is distributed through a single feeder. In this case, let I equal 1000 amperes. Equation (1) gives annual feeder cost for constant distributing distance (D). This equation may be expressed as

$$C_v = a\,m + b/m + c/m$$

In these equations the terms a and b will be the same as for constant distributing distance. The term b/m represents the carrying charges on that part of the generating plant, transmission line and substation investment necessary to carry the peak distribution losses. During the peak load the distributing distance will be D (as defined above), so that b remains unchanged. The value of c, however, will be different for variable distributing distances since c/m represents the operating expenses for the heating losses twenty-four hours per day during which time distributing distance has changed several times as substations are put on and taken off the line. The value of c/m may be determined by dividing the twenty-four hours into periods within which the number of substations in operation is unchanged. On the accompanying load chart it will be seen that there are eight steps to the capacity curve and consequently for this case there are eight periods of constant capacity. Each of these periods may be treated separately and the value of c/m set down.

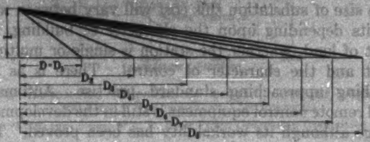

Fig. 5

For the type (*b*) feeder c/m becomes $\frac{c}{3\,m}$ because of distributed load.

In Fig. 5, D_1, D_2, D_3, etc., represent distributing distances corresponding to the eight periods or steps into which the capacity curve of the system has been divided. I, which is a definite proportional part of the rated capacity of the substation, is of course constant. L approaches unity in proportion as the operator is able to make the capacity curve approach more nearly the actual load curve. During twenty-four hours the value of $\frac{c}{3\,m}$ for the distance D will be the summation of the values of $\frac{c}{3\,m}$ for each of the eight periods as follows:

$$(1)\quad \frac{c}{3\,m} = t_1 \times 2.92 \times I^2 L_1\, e\, D_1 \frac{(10.35)}{m} \times D/D_1$$

$$(2)\quad \frac{c}{3\,m} = t_2 \times 2.92 \times I^2 L_2\, e\, D_2 \frac{(10.35)}{m} \times D/D_2$$

etc.,

in which t_1, t_2, t_3, etc., are the percentages of time represented by each period. Hence for the distance D, twenty-four hours per day

$$\frac{c}{3\,m} = 2.92\, I^2\, e\, D \frac{(10.35)}{m} (t_1 L_1 + t_2 L_2 + \ldots)$$

Thus L in the original equation simply becomes the weighted average loss factor of the several operating periods, approaching unity in value. For the conditions represented by the load and capacity curves used in this illustration L is about 0.90. Looking at the problem in a different way, we may say that the feeders are fully loaded a much larger part of the time under this method of operation than for constant distributing distance. From an economic standpoint, therefore, larger feeder sizes are warranted because the load factor on this copper is larger. With this difference, the equations and curves already presented for type (*b*) feeders with constant distributing distance apply to the case of variable distributing distances.

Example: Using the same values for D, e, f, I and p, as used in the previous examples for constant distributing distance, *viz.*: $D = 7920$ ft., $e = \$0.008$, $f = \$0.0186$, $I = 750$ amperes, $p = \$23.00$, and assuming 0.90 as the value of L

$$m = 1{,}570{,}000$$

$$C_v \text{ (minimum)} = \$1{,}690.$$

$$E_v = 19.6 \text{ volts.}$$

5. GENERATING PLANT, TRANSMISSION LINE AND SUBSTATION INVESTMENT

Generating plant investment is independent of the distribution and substation layout, where power is supplied from a central station. In making distribution calculations, the generating plant investment per kilowatt should of course include a proper amount for spare capacity. On this basis the investment will lie within the limits of \$90 and \$150 per kilowatt (undepreciated) and the carrying charges \$11.70 to \$22.50 per year.

The investment in transmission lines will vary greatly with the number and size of substations and with the arrangement of the lines. It is of course apparent that this investment will increase with the number of stations. Should the same factor of safety be required for each of many small substations as is now required of the larger substations, the increase in investment would be in some cases nearly in direct proportion. This, however, should not be the case since the failure of one small substation is of smaller consequence. If there be a very large number of substations, for example forty or more in a city such as Cleveland, it is possible that two substations might be fed safely from a single transmission line. It would appear likely that a group system could be used to advantage in cities with many small substations. This would make possible a large factor of safety without an unduly large investment in transmission lines.

In any event it becomes evident that the transmission layout must depend largely upon the seriousness of a substation failure during the peak load. This question may be answered by reference to the voltage drop equations that have been given, provided of course, that there be the proper amount of copper to meet the condition of maximum economy. The limiting condition will be found in the case of multiple-unit stations since the feeder sizes are necessarily smaller than for single-unit stations. The proper cross-section for a type (*b*) feeder would in no case be less than 1,200,000 cir. mils per 1000 amperes. The total voltage drop (peak) would be 37 volts (assuming a four-rail return circuit, properly bonded or welded, 3×10^{-6} ohm per ft.) for a distributing distance of 6500 feet. If now a substation fails, about the worst condition will be doubling the load on the feeder and doubling the distance in which case the drop becomes 148 volts. On the average city system today there is not the proper amount of feeder copper for maximum economy. Furthermore, distributing distances are great, generally two miles or more. It therefore follows that the shutdown of a substation of such a system during the peak load becomes a matter of serious consequence resulting in trolley voltages so low that it is perhaps impossible to handle the traffic. The development of the automatic substation will without doubt lead to distributing distances (for peak load) of 6500 feet or less in larger cities. It would therefore appear that the failure of a single substation on such a system should not reduce line voltages to a point where the operation of cars would be hampered.

It is next to impossible to generalize on the per kilowatt investment in transmission lines. From 25 per cent to 50 per cent of the cost of underground lines is for conduit. If power is purchased from a central station company the investment allocable to the railway load will be substantially less than it would be if the railway company owned its own generating station and transmission lines. In such cases the transmission line investment would not necessarily be increased unduly by the installation of many small railway substations. In any event it is probably fair to say that this cost, including the distributing stations of the central station company, should not exceed \$30 per kilowatt for underground construction in large cities even though the substation be as small as 1000-kw. capacity. The carrying charges on this amount would not exceed \$4 per kilowatt per annum. The limits for the carrying charges on generating plant and transmission lines (including power company distributing stations) may be put approximately at \$14 and \$27 per kilowatt per year. (The term "carrying charges" is sometimes used to include standby operating expenses; the term is not so used here).

In this analysis the demand charge of the power company, if the railway company purchase power, will take the place of the carrying charges discussed above. In most cases this greatly simplifies analysis of a particular local situation. Similarly the power company's kilowatt-hour charge, will be used in place of "operating expenses for generating plant and transmission lines."

The item of investment which will vary through the widest range with the number of distributing points for a given load, is the substation investment. For any one size of substation this cost will vary between wide limits depending upon the character of building, the cost of land, whether the station is single or multiple-unit and the character of control. There is as yet nothing approaching standard practise. Automatic and remote control equipment is still in the development stage although its workability has been proved. The writers are in accord with the opinions expressed by the "Power Generation" Committee of the American Electric Railway Association in its 1921 report[3] as follows:

> The success of the automatic idea having been proved, the principal problem at the present time is that of deciding on the most satisfactory size and number of units for a station, to secure the greatest economy while not sacrificing the quality of service. (Pg. 33.)
>
> Apparently the ideal scheme of installation is to use the smallest possible single-unit stations located at relatively short distances from each other in a very simple and small building. This type of construction will undoubtedly find much favor in the eyes of the rapid transit lines in the small cities where service requirements are not so exacting and where the traffic density never reaches a point where a service interruption results in a more or less large monetary loss. (Pg. 33.)
>
> Experimental work is now being conducted to find a solution on a full automatic basis, for the difficulties outlined above, for both machine and feeder control as encountered in Metropolitan service. However, where warranted a system of remote control superimposed upon that of the automatic control will solve the difficulties. By this method the machines could be operated dependent upon the balance between the conversion efficiency and operating cost per car mile, dependent upon average trolley voltage conditions. In this manner the operation of machines may be controlled from a dispatching center, simulating manual conditions but with greater system flexibility. (Pg. 50)

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[3] This committee report contains a good statement of the case of substation costs in which are shown the various factors determining these costs.

The cost of remote control over telephone wires will be so small as to be almost negligible. It need not, therefore, be specifically included in this analysis although its use, in cities at least, should be contemplated.

The curves of Fig. 6 show in a general way the limits of substation investment (without land). The upper (multiple-unit) curve is based largely upon Cleveland substation costs. The buildings for these stations are spacious, and the construction elaborate. The exteriors are suitable for residential districts. There are toilet and heating facilities and decorative lighting fixtures. The lower (single-unit) curve on the other hand represents minimum cost based upon the smallest and simplest buildings possible.

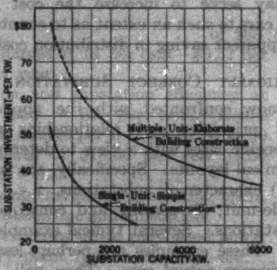

FIG. 6—AUTOMATIC SUBSTATION COSTS (WITHOUT LAND), 60-CYCLE SYNCHRONOUS CONVERTERS

*From 1921 report of A. E. R. A. Power Generation Committee

Consideration of investment charges involves the question of reserve capacity. The per kilowatt investment used in an analysis of this kind must be large enough to provide for this reserve capacity. The amount of such reserve of course depends upon the system of rating of electrical equipment. The Westinghouse Company rates its synchronous converters to permit 50 per cent overload for two hours. This amounts to 50 per cent reserve if the installed rated capacity is not less than the peak load requirements. The argument has been advanced that with small single-unit substations it is not possible to have the same reserve capacity for any one substation area excepting by the installation of a prohibitive amount of copper. This is not the case where distributing distances are not more than about 6500 ft. and feeders are of the proper size. This has already been pointed out. If under these conditions one station fails, its area will be fed through the tie lines (type (*b*) feeders) from two or more adjacent substations, the reserve capacity of which will be more than sufficient to carry the additional load. It may be seen from the previous equations and calculations that the total distribution cost is only 15 per cent more for this type of feeder than for the theoretical tapering feeder and in many cases this latter type of feeder (type (*c*)) could not be used regardless of the size or type of substation. Provided the saving in any particular case resulting from increasing the number of substations from a few multiple-unit stations to a larger number of single-unit stations is large, then the argument of the superior reserve characteristics of multiple-unit stations, is no longer valid. Indeed the reverse may hold true, because there is less chance of the failure of two equipments which are several thousand feet apart than of two machines in the same station and there may be some simplification of control equipment.

6. OPERATING EXPENSES OF GENERATING PLANT, TRANSMISSION LINES AND SUBSTATIONS

It should be pointed out here that the value of e in the foregoing computations includes all items entering into the cost of direct-current power excepting interest, depreciation and taxes, and that due allowance must be made for transformer, transmission and conversion losses so that e represents operating expenses per direct-current kilowatt-hour at the railway substation bus.

Generating plant operating expenses are independent of the distribution layout. Transmission line operating expenses will in general vary with the mileage in somewhat the same proportion as transmission investment. Unless there be a large difference in the transmission mileage required for two different distribution layouts it is probable that this item of expense may be neglected in making a comparison. It should not exceed 4 per cent of operating expenses even for very small substation installations.

The total converter substation operating expense (including maintenance) for the Cleveland manual substations is less than $0.0009 per d-c. kw-hr. Of this amount, approximately 30 per cent is for maintenance and 10 per cent for supplies; the remaining 60 per cent is for operator's wages. These figures are fairly typical, excepting that the labor cost is somewhat low because of large capacity stations. In the case of automatic control this last item is eliminated excepting for the labor of inspection and cleaning. This, together with maintenance, will increase somewhat with an increase in the number of substations used to serve a given load. For one thing, employes will have to spend more time in going from one substation to another. The transportation cost for men and supplies will also increase. The average manual substation capacity in Cleveland is approximately 6000 kw. for which the operating costs, exclusive of operators' wages are approximately $0.00036 per kw-hr. If the total operating expenses be assumed to be $0.008 per d-c. kw-hr., which is a low figure, then substation operating expense will be only 4.5 per cent. Approximately half of this amount is for labor and the rest for supplies and materials, the cost of which should not change appreciably for a larger number of small substations. Should the Cleveland system be supplied with power from forty 1000-kw. substations, it is conceivable that the labor cost for maintenance and inspection might increase the total substation operating cost to 7.0 per cent. This would mean more than doubling present maintenance labor costs. Due to the fact that the automatic substation has not as yet come into general use, it is impossible to present precise data on operating costs. The above figure is only a guess as to an upper limit.

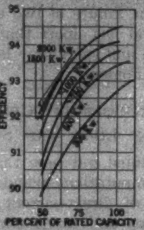

FIG. 7—COMBINED EFFICIENCIES

Three phase, 60-cycle synchronous converters, with three single-phase transformers (Westinghouse).

Ratings based on 50 per cent overload for two hours, starting hot.

Another factor requiring consideration in a study of this kind is substation efficiency. Presumably at the time of peak load all substations will be operating at approximately full rated load and consequently at about maximum efficiency, no matter what scheme of layout may be determined upon. The combined efficiency of Westinghouse railway 60-cycle converters with their transformers increases about 2.5 per cent from one-half to full load. This range is somewhat less for the larger sizes (over 1000 kw.) and somewhat greater for the smaller sizes. Should the distribution system be so laid out as to necessitate operation of converters at an average of 75 per cent of rated load instead of full load, there would be a loss of 1 per cent of operating expenses per kilowatt-hour. If these operating expenses be $0.008, then for cities the size of Cleveland, or Detroit or St. Louis, this loss would amount to about $11,000 per year. It will be seen that this is small in comparison with total distribution costs. It is possible in some instances that smaller distributing distances and consequent decreases in distribution cost might justify the operation of certain substations at considerably less than rated capacity during off-peak hours instead of shutting down the substations and thereby increasing the distributing distances.

There is a considerable difference in the efficiency of converters with their transformers between the small and large sizes. The Westinghouse 300-kw. converter with transformers is 1.4 per cent less efficient than the 1000-kw. equipment at full load and 1.8 per cent less at one-half load. There is less difference between the larger sizes. In determining upon a distribution layout and consequently upon the size of converters this difference in efficiency must be considered. Suppose for example one layout calls for twenty-one 1000-kw. single-unit stations with an average distributing distance of 6000 feet and that the distributing cost figured out to be $56,000 per year; and another layout calls for seventy 300-kw. stations with an average distributing distance of 2500 feet so that the distributing cost was found to be $22,000. With a load factor of 40 per cent and power operating expenses of $0.008 for both cases, this difference in size of equipment alone would add more than $8,000 to the cost of power, which would be an offset to the saving in distribution cost. It must, of course, be borne in mind that other factors such as increased carrying charges and operating expenses may serve to increase the cost of power used by the cars to such an extent as to counterbalance the above apparent saving in distribution cost.

7. ECONOMICALLY CORRECT SUBSTATION LAYOUTS

We are now confronted with the application of the several principles and relationships set forth above, to specific cases with a view to determining the most economical layouts. Specifically, the problem is two-fold, (1) character of substations, *i. e.*, multiple-unit or single-unit; (2) spacing and consequently the size of substations. Several typical examples will be considered. These examples are perhaps less complex than the average actual case. They will, however, make possible the formulation of some general conclusions which, it is hoped, will prove of value in the solution of the practical problems of distribution.

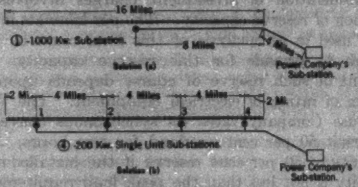

FIG. 8—SINGLE INTERURBAN LINE

Schedule speed, 20 miles per hour.
Peak headway 12 minutes.
Number of cars on line, eight (peak).

(a) *Single Lines*

CASE 1. Single Interurban Line. (See Fig. 8).

Length—16 miles, single track, open country.
Maximum load (with one substation) 1000 kw. 640 volts.
Load uniformly distributed over line.
Load Factor 35 per cent.
Loss factor for system 20 per cent.
High resistance roadbed—crushed stone ballast, exposed rail, bonded joints, 90-lb. rail.
No negative feeders.

Power purchased, delivery high-tension (22,000 volts) at power company's distributing substation.

Power rates— demand charge: flat rate 1.25 per kw. per month.

Kilowatt-hour charge: flat rate—$0.0075.

Substations, full automatic.

Cost of feeder in place—$0.155 per lb.

Solution (*a*) One 1000-kw. substation at middle of line, two 500-kw. units.

Cost of substation ($50.00 per kw.)........	$50,000
Cost of transmission line	
4 miles—$2100 per mile (includes poles)	8,400
8 miles—$1200 per mile (using trolley poles)...........................	9,600
	$68,000
	or $68.00 per kw.
Carrying charges at 14 per cent—$9.52 per kw. per year........................	$9.52
Transmission and substation efficiency at peak load = 83 per cent. Hence demand charge per d-c. kw-hr. is $1.50 per month or $18.00 per year (1.50 = 1.25 ÷ 0.83....................	18.00
Total carrying charges on generating plant, transmission line and substation.......	$27.52
Operating expenses up to purchased power delivery point (kw-hr. charge)—a-c....	$0.0075
Operating expenses (kw-hr. charge)—d-c.... (Efficiency of transmission and substation—81 per cent)	0.00927
Transmission line and substation operating expenses per kw-hr.—d.c...............	0.0012
	$0.01047

$L\,e = 0.002094$

Type (*b*) feeder cross-section (from curves) 780 amperes = 1,187,000 cir. mils. (one 1,000,000-cir. mil cable and 3/0 trolley)

Peak feeder drop[4] (8 miles = 144 volts

Rail and ground resistance (G) (2 rails) = 5.5×10^{-6} ohm per foot.

Peak distribution circuit drop[4] = 235 volts

Minimum line voltage[4] = 640 − 235 = 405 volts.

It should be pointed out that the condition of uniform distribution is satisfied over a period of time (*i. e.* car headway or longer period) but never instantaneously. Hence the above minimum voltage will not be the lowest instantaneous voltage. Were there a very large number of cars on the line, these two voltages would be practically the same. With eight cars, two miles apart and one of them at the end of the line the minimum instantaneous voltage would be 345 volts. It is possible to operate the average interurban car at this voltage.

The minimum annual cost of distribution for the entire sixteen miles of this interurban line is $18,000 (determined from the equations), based upon the type (*b*) feeder. Had this been a type (*c*) feeder (*i. e.*, tapering section) the theoretical minimum cost would have been $1,840 less. Hence the cost would be between $16,160 and $18,000 depending upon the number of steps by which the section of the feeder be decreased between the substation and the end of the line. The actual cost would be about $17,000.

Solution (*b*)—Four 200-kw. substations, one 200-kw. unit per station.

Cost of substations ($70.00 per kw.).........	$56,000
Cost of transmission line	
4 miles—$2100 per mile.................	8,400
14 miles—$1100 per mile.................	15,400
	$79,800
	$100.00 per kw.
Carrying charges at 14 per cent.............	$14.00
Transmission and substation efficiency at peak load—82 per cent, demand charges.......	18.28
Total carrying charges.........	$32.28

During the peak load period all substations will operate continuously at about full load since there will always be two cars in the distributing zone of each substation. During the off-peak periods the load may be carried in one of two ways. One or two of the substations may be operated continuously distributing over correspondingly wider zones, or all four substations may be operated intermittently as cars pass through their zones, by means of the low-voltage relays. Under the first plan distributing cost will be higher and under the second plan substation operating efficiency will be lower. Both plans will be considered here.

Assume that as the system load decreases, substations are taken off the line in the following order: No. 2, No. 4, No. 1, and No. 3. It should then be possible to keep each substation loaded on the average to at least 70 per cent of rated capacity. Whatever this average loading may be it must necessarily be substantially better than in the case of a single substation having two 500-kw. units. At full load the difference in efficiency on account of size of units will be about 1 to 2 per cent. The difference in efficiency due to the machines being loaded on the average to different percentages of rating will be of this same order, but if anything a little less. It is probable, however, that the net difference in substation efficiency between the larger two-unit station and the four smaller single-unit stations (operated under the plan of taking stations off the line as the load decreases) will be less than 1 per cent. Transmission line efficiency will not be different for solution (*b*) as against solution (*a*) since the *average* distance is the same. The combined transmission and substation efficiency will therefore be taken at 80 per cent.

---

[4] Average during peak period, *i. e.*, corresponds to 780 amperes uniformly distributed.

The item of transmission line and substation operating expense will be increased as against the cost for the single two-unit station. There will be six miles more transmission line and the cost of inspection and maintenance of substations will be greater for reasons already pointed out. This item will, therefore, be taken at \$0.0014 per d-c. kw-hr. Thus total operating expenses become \$0.01080 per d-c. kw-hr. as against \$0.01047 for solution (*a*).

Loss factor will be taken at 0.60. $L\,e$ is, therefore, 0.0065. Type (*b*) feeders (*i. e.*, uniform cross-section) will necessarily be used between substations in this solution because of the method of operating the substations. For the sake of simplicity, uniform section feeders will also be used on the two dead-ended sections at either end of the line.

Peak distribution losses for solution (*a*) will be

$$0.001\,\frac{I^2}{3}\,D\left(\frac{10.35}{m}+G\right)=H_a=2\times 0.001 \times\frac{780^2}{3}\times 8\times 5280\left(\frac{10.35}{1{,}187{,}000}+5.5 \times 10^{-6}\right)=247\text{ kw.}=24.7\text{ per cent}$$

The power used by the cars in solution (*a*) is therefore

$$1000-247=753\text{ kw.}$$

The peak distribution losses in solution (*b*) will be

$$H_b=8\times\left[0.001\times\frac{I^2}{3}\times 2\times 5280\left(\frac{10.35}{m}+5.5\times 10^{-6}\right)\right]$$

in which

$$m=0.577\,I\times\sqrt{\frac{2820\,p+24.7\times 10^6\,L\,e}{f}}=2122\,I$$

Hence

$$H_b=28.2\,I^2\left(\frac{10.35}{2122\,I}+5.5\times 10^{-6}\right)=\left(I\times\frac{640\times 8}{1000}\right)-753$$

I = 151.8 amperes. m = 322,000 cir. mils (including trolley)

H_b = 24.4 kw.

Total power = 24.4 kw. + 753 kw. = 777.4 kw.

H_b = 3.14 per cent.

The minimum annual distribution cost for the 16 miles becomes:

$$C\text{ (min.)}=8\left[0.000225\times 151.8\times(2\times 5280)\times\sqrt{0.0186\,(32.28+56.94)}+\frac{151.8^2\times(2\times 5280)\times 5.5\times 10^{-6}}{3}\times(0.001\times 32.28+8.76\times 0.0065)\right]=\$4008$$

Following is a comparison of the total power costs for solutions (*a*) and (*b*):

COMPARISON OF TOTAL POWER COSTS

Solution (*a*)	
Power actually used by cars:	
Investment charges—753 × \$27.52	\$20,722.00
Operating expenses—2,300,000 × 0.01047	24,081.00
	\$44,803.00
Distribution cost	17,000.00
	\$61,803.00
Solution (*b*)	
Power actually used by cars:	
Investment charges—753 × \$32.28	\$24,307.00
Operating expenses—2,300,000 × 0.0108	24,840.00
	\$49,147.00
Distribution cost	4,008.00
	\$53,155.00
Saving in favor of solution (b)	\$8,648.00

If, instead of cutting some of the substations off the line entirely, during off-peak periods, all substations be operated by the low-voltage relays so as to start up when a car comes within their distributing zones, then the above figures for solution (*b*) must be changed somewhat. In the first place, the average substation efficiency will be lower by reason of the stopping and starting losses. The difference is probably of the order of 5 per cent. To offset this there is some saving in cost, since the distribution distances during the off-peak periods will be the same as during the peak periods. Expressing this in the mathematical terms that have been used above, loss factor (L) becomes 0.20 instead of 0.60 as used for the other method of operation.

$$m=0.577\,I\sqrt{\frac{2820\,p+24.7\times 10^6\,L\,e}{f}}=1607.6\,I$$

$$H_b=28.2\,I^2\left(\frac{10.35}{1610\,I}+5.5\times 10^{-6}\right)=\frac{(I\times 640\times 8)}{1000}-753$$

I = 153.1 amperes.

H_b = 31.23 kw.

Total power = 31.23 + 753 = 784.23 kw.

H_b = 3.98 per cent

$C_{(\text{min.})}$ = \$3054 or \$955 less than for the other method of operation. Operating expenses per d-c. kw-hr. become \$0.0114 or an increase of \$0.0006

$$2{,}300{,}000\times \$0.0006=\$1380.$$

It is apparent that in the case under consideration there is very little difference in cost between the two methods of operating. Under such conditions it would perhaps be better to adopt the first method (*viz.* cutting some stations off the line entirely during light load periods rather than having these stations operate intermittently as cars come within their zones), for the reason that the additional copper provides that much larger factor of safety and also because the intermittent operation is somewhat harder on equipment.

It is apparent that a still further decrease in the size of substations, while perhaps netting some slight saving, would probably be unwise since the machines would be too small to carry the heavy swings when there are two cars in a distributing zone.

Total Power Cost as a Function of Distributing Distance—Single Lines.

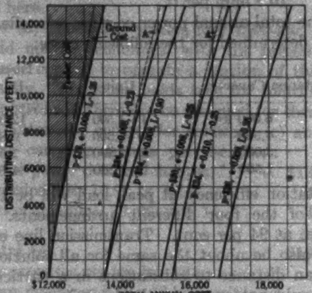

FIG. 9—ANNUAL COSTS

One-mile double track.
Uniform traffic.
Power consumption by cars, 260 kw. peak.
Return circuit resistance $= 2.5 \times 10^{-6}$ ohms per foot
Feeder investment, $0.155 per lb.
D-c. bus voltage = 600
Type (b) feeder.
Curves *A*—two-mile double track power consumption by cars, 130 kw. peak per mile.

In Appendix III the equation for D in terms of the other variable factors is derived for type (b) feeder.

This relationship is presented in the form of curves (Fig. 9). These curves serve to show the relation between distributing distance and total annual cost of power for one mile of track on which there is a uniform distribution of traffic. It will be noted that the curves have been drawn for several different values of p (generating plant, transmission line and substation investment carrying charges), for different values of e (operating expenses) and for different traffic densities (viz., 130 kw. per mile and 260 kw. per mile). From these curves it is possible to generalize to some extent upon the question of how far we may go in reducing distributing distances and still make for saving in power cost. Take for example the curve for which $p = \$24$, $e = 0.008$, $L = 0.25$, $G = 2.5 \times 10^{-6}$, and power used by cars is 130 kw. per mile. Were it possible to reduce distributing distance on the single line under consideration from 13,000 feet to 5,000 feet by the installation of additional substations, but without increasing the per kilowatt investment or the operating expenses, the saving would be $420 per year per mile of track. As a matter of fact, the investment per kilowatt would increase with the number of stations, and the question arises how far may we go in increasing investment per kilowatt and still produce a saving in the cost of power. Provided operating expenses remain substantially the same, it is clear that p may be increased to $27 per kilowatt per year before the savings from decreased distance would be offset by increased carrying charges. The increase is $3 which capitalized at 14 per cent, amounts to $21.40. Investment in generating plant will presumably be the same for all solutions of this distribution problem. Hence we may spend up to $21.40 per kilowatt on transmission lines and substations before the saving is wiped out. Suppose now that for a particular railway system, or better yet, for a particular section of this system a 4000-kw. multiple-unit station will be sufficient to feed an area such that the distributing distance on the several single lines in this area will be 13,000 feet. Suppose also that the system be such that a 1500-kw. multiple-unit station will be sufficient to feed an area such as to make the distributing distance 5000 feet. According to the curve for multiple-unit substation costs the difference in cost would be about $15 per kilowatt. Suppose now that the increase in transmission line investment is $3 per kilowatt, making the total increase $18 of which 14 per cent amounts to $2.52. By interpolation between curves it may be seen that the cost of power for the one mile of track will be approximately $7330 as against $7420 for the larger substation. The difference is $90 per year. If operating expenses, after taking account of any difference in transmission and substation efficiency, be substantially greater per kilowatt-hour for the smaller substation, then the above saving of $90 per mile will be correspondingly less. A difference of 1.5 per cent in the substation efficiency would more than offset this $90.

The above analysis is based upon constant distributing distances twenty-four hours per day. Should single-unit stations be contemplated, some of which would be shut down during off-peak periods, the curve or equations for a loss factor (L) of say 0.60 or more would be used.

The above example serves to show that the margin of saving is small for the range of distributing distances that would obtain in large cities. It shows that the investment in transmission lines and substations must be held down to bed rock minimum if there is to be any appreciable saving in the total cost of power. Furthermore, it is evident that the efficiency of equipment and all other factors entering into the total operating expenses per direct-current kilowatt-hour must be carefully weighed before the adoption of small units.

In weighing these questions of cost there is another factor which must not be forgotten. Many railway companies have found it necessary to make comparatively large investments in insulated negative feeders and in other provisions for reducing stray currents and the consequent electrolytic corrosion of underground structures. In the foregoing analysis no account has been taken of negative feeders or other special mitigative measures. In some instances this item of cost has been large. The City of Winnipeg has recently installed the three-wire system of distribution in order to comply with a law recently passed by the Province of Manitoba which limits the allowable track drops. In considering the merits of a large number as against a small number of substations, this factor must be given weight. If electrolysis is a serious matter in a particular locality, it may prove the deciding factor in favor of the larger number of substations.

(b) *City Networks*

It is not possible within the limits of a paper of this kind to analyze comprehensively the entire system of any one large metropolitan city. Even if this were possible it would be of doubtful value. In lieu of such an analysis, a simple illustration will be used in which the values used for the different determining factors are typical average values for cities such as Cleveland (or Detroit or St. Louis). Were a careful analysis made for a particular city, it would be necessary to treat each line separately and to find total costs by adding up these single line results. Hence if we would generalize, it is perhaps sufficient to treat a single line on which average conditions obtain.

If the railway system be a single line (an interurban for example) or, if a city network, be considered as composed of single lines so that each substation feeds in two directions only (*i. e.,* one dimension) then distributing distance will be inversely proportional to the number of substations in operation. If the railway system be a very dense network so that every substation feeds in four directions or in effect feeds an area rather than a single line, then distributing distance will be inversely proportional to the square root of the number of stations. In the case of a large city network the relationship between distributing distance and number of substations will be somewhere between the two extremes set forth above, and as the number of substations is increased the relationship for single lines will be more nearly approached.

In the present example distributing distance has been found from the formula:

$$D = K \times (\text{Substation Capacity})^{0.75}$$

This formula expresses approximately the conditions in Cleveland. It is half way between the relationship for a single line and that for a very dense network or area.

CASE 2. Heavily loaded metropolitan system.

Excepting purchased power rates the following values are approximately correct averages for Cleveland. In place of Cleveland power rates more typical values are used.

1. Average peak power required per mile of double track—260 kw. or 0.0492 kw. per ft.
2. Substation bus voltage—600.
3. Yearly load factor—0.40.
4. Yearly loss factor for system—0.25.
5. Demand charge at power company's distributing substations—\$1.00 per kw. per month. (Unity power factor).
6. System power factor unity.
7. Kw-hr. charge at power company's distributing substations—\$0.006.
8. Type (b) feeders only.
9. Effective return circuit resistance (G) = 2.5×10^{-6} ohm per ft.

The total annual power cost for one mile of track will be determined for the following cases:

Substation Capacity		Units	Distributing Distance
(a)	6,000 kw.	4—1,500	12,000 ft.
(b)	4,500 “	3—1,500	9,800 “
(c)	3,000 “	2—1,500	7,500 “
(d)	1,500 “	1—1,500	4,700 “

Substation efficiency at peak load will be the same for all of the four different arrangements. It will be taken at 94 per cent. Transmission line efficiency should also be about the same for all solutions since the mean distance to substations in a particular district should not vary greatly for a larger number as against a small number of stations. This will be assumed to be 97 per cent. Thus generating plant carrying charges per kilowatt (direct-current) become

$$\frac{\$12.00}{0.94 \times 0.97} = \$13.16$$ (*i. e.* demand charge corrected for losses)

It will be assumed that the average distance from the power company's distributing station to the railway substations will be substantially the same for the different layouts. This distance will be taken at two miles and the following transmission line capacities will be used:

(a) 6000 kw. substation 3—4/0 cables
(b) 4500 “ “ 3—2/0 “
(c) 3000 “ “ 2—4/0 “
(d) 1500 “ “ 1—4/0 “

The cost of cable ducts will vary from \$0.50 per duct foot for nine duct banks to \$1.25 per duct foot for three duct banks. As the size of substations is decreased, and in consequence the number increased, it will not be possible to utilize to the same extent the main artery duct subways of the power company, with the result that the cost per duct foot will be greater for the smaller substations. The following costs per duct foot will therefore be used: (a) \$0.65; (b) \$0.77; (c) \$0.89; (d) \$1.00. To these costs will be added \$0.15 per foot for pulling and splicing and the cost of the cable itself which will be taken at \$1.45 per foot for 4/0 cable and \$1.11 per foot for 2/0 cable, both being three-conductor lead-covered 11,000-volt cables. Thus the investment in transmission lines per kilowatt of substation capacity becomes: (a) \$11.91; (b) \$14.29; (c) \$17.53; (d) \$18.30. In the case of the 1500 kw. station there is no duplicate service but in this case the distance between substations is small and the shutting down of one substation is not, therefore, of serious consequence for reasons already pointed out elsewhere.

The average efficiency of transmission lines over a period of time will be about 98.5 per cent. This will not vary appreciably for the several solutions to be compared here.

Solution (*a*)—6000-kw. station-four-1500-kw. units.

It would not be economical with the present cost of automatic control to operate a station of this size automatically. The same holds true for solution (*b*). Manual control will therefore be assumed for these two cases and automatic control for solutions (c) and (d).

Investment carrying charges per d-c. kw.:

Purchased power demand charges	\$13.16
Transmission lines 11.91 × 0.14	1.67
Substation (manual) 30.00 × 0.14	4.20
Total (*p*)	\$19.03

Operating expenses per kw-hr.—d-c.

With four machines it should be possible to keep load on each machine near capacity with resultant high efficiency, *i. e.*, 91 per cent.

Purchased power kw-hr. charge—

$\frac{0.006}{0.985 \times 0.91} =$	0.0067
Substation and transmission line operation	0.0011
Total (*e*)	0.0078

The substation will be operated twenty-four hours per day and distributing distance will be constant. Hence *L* for the distribution system may be taken as 0.25.

Annual cost (from curves) for one mile of double track \$13,270

Solution (*b*)—4500-kw. station—three—1500-kw. units.

Investment carrying charges per kw.—d-c.

Purchased power demand charge	\$13.16
Transmission lines 14.29 × 0.14	2.00
Substation (manual) 34.00 × 0.14	4.76
Total (= *p*)	\$19.92

Operating expenses per kw-hr.—d-c.

Average substation efficiency—90.5 per cent.

Purchased power kw-hr. charge

$= \frac{0.006}{0.985 \times 0.905} =$	0.00674
Substation and transmission line operation	0.00120
Total (= *e*)	0.00794

The substation will be operated twenty-four hours per day and distributing distance will be constant. $L = 0.25$.

Annual cost (from curves) for one mile of double track \$13,380

Solution (*c*)—3000-kw. station, two—1500-kw. units, automatic—remote control.

With substations of this size it is not desirable to operate all substations during the light load periods because to do so would mean a sacrifice of substation efficiency that would more than offset the difference in distribution cost. It should be possible to obtain an efficiency of 90.5 per cent by cutting out altogether some substations during the light load periods, that is, to equal the efficiency of the 4500-kw. station operating twenty-four hours per day. This performance cannot, of course, be had if there are very heavy load fluctuations and the machines are allowed to start and stop many times per day. This starting and stopping may easily result in an efficiency decrease of 5 per cent which under no circumstances can be justified on a large city system for it would be better and cheaper to use larger stations and distribute longer distances. Unless the load conditions be very unusual it should be possible to start and stop machines by remote control only as the regular system load increases or decreases. This method of operation will be assumed both for this solution and for solution (d). Inasmuch as the substation may be shut down a part of the time (*e. g.*, during the early morning hours), loss factor (*L*) will be greater, that is, the feeders will be loaded more during the light load periods than they would be if all substations were operated continuously. The exact value of *L* for a case such as that under consideration may of course be found for any particular load curve and plan of operation. It will suffice here to assume a value of 0.40.

Investment carrying charges per kw.—d-c.

Purchased power demand charge	\$13.16
Transmission lines 17.53 × 0.14	2.45
Substation (automatic) 43.00 × 0.14 (heating, toilet facilities, etc. eliminated)	6.02
Total (= *p*)	\$21.63

Operating expenses per kw-hr.—d-c.

Average substation efficiency—90.5 per cent

Purchased power kw-hr. charge

$\frac{0.006}{0.985 \times 0.905}$	0.00674
Substation and transmission line operation	0.00085
Total (= *e*)	0.00759

Annual cost (from curves) for one mile of double track	$13,300

Solution (d)

Investment carrying charges per kw.—d-c.	
Purchased power demand charge	$13.16
Transmission lines 18.30 × 0.14	2.56
Substation (automatic) 53.00 × 0.14	7.42
Total (= p)	$23.14
Operating expenses per kw-hr.—d-c.	
Average substation efficiency—89 per cent	
Purchased power kw-hr. charge— $\frac{0.006}{0.985 \times 0.89}$	0.00685
Substation and transmission line operation	0.00090
Total (= e)	0.00775

In this case loss factor (L) will be considerably increased over the value used in solution (c) since many of the substations will be operated only through the peak (see Fig. 4.) L will be taken at 0.60.

Annual cost (from curves) for one mile of double track	$13,650

The foregoing calculations are all based upon the type (b) feeder since it is the most common. It is hardly necessary to repeat for the other types since the only effect would be to increase or decrease distribution costs and therefore change slightly the slope of the curves without materially changing the relative results of the several solutions. It is believed that whatever conclusions that may be drawn from these figures will apply equally to a system employing all types of feeder.

8. CONCLUSIONS

(a) The economically proper size of feeder where, as in cities, distributing distances are at most three or four miles, is such that the maximum voltage drops are too small ever to interfere with proper operation of cars. The difference in total annual cost between a properly proportioned feeder system and one designed to give the minimum voltage for satisfactory car operation is considerable, and should warrant a fairly careful examination of feeders and their loads at sufficiently frequent intervals to permit proper changes from time to time to take care of changing conditions. In general it may be said that in cities sufficient feeder copper is not used. This does not hold true to the same extent for interurban lines where distributing distances are great because economically proper trolley voltages more closely approach the minimum voltages necessary for car operation. This was brought out in the analysis for the single interurban line.

(b) The economic justification of the automatic substation is a reduction in distribution cost. In other words, the only reasons for adopting automatic control is to permit the use of small substations (3,000 kw. or less), because for such small substations the operating costs for manual control are prohibitive. The additional investment for automatic control is warranted approximately in proportion to distributing distance. Its principal field is, therefore, the interurban railway or long rapid transit line and also long electrified steam roads. In cities, on the other hand, the economic advantages of the automatic substation are relatively small because distribution cost is a correspondingly small part of total cost. For this reason automatic substation efficiency is of particular importance on city systems. A reduction of 2 or 3 per cent in the efficiency for automatic as against manual control may more than offset any saving that results from decreased distributing distance. The efficiency of automatic substations varies through wide limits for different load conditions and for different methods of operation.

(c) In a city district in which there are wide fluctuations in load, and in which full automatic control is used so that machines are started and stopped entirely by line voltage and load conditions, the average efficiency of a substation over a period of time may be reduced by as much as 5 per cent largely because of the frequent starting and stopping of machines. In many such cases it should prove far better to start and stop machines by remote control according as the average trend of the load is up or down. This may mean that the machines will be in operation for many short periods during which the load is far below their rated capacity, but even so, the reduction in efficiency resulting from such operation at a low percentage of capacity, will be of a smaller order than the reduction that may result from starting and stopping. If such a method of operation results in an average efficiency decrease of say 2 per cent or even less, it may be found more economical to shut down the substation altogether during off-peak periods. Thus it is apparent that the method of operation to be adopted and the substation efficiency that will result from such operation, must be thoroughly analyzed; otherwise, the use of the automatic substation may serve only to increase the cost of power. It is believed that in large cities it will prove necessary to adopt some form of remote control in conjunction with automatic control.

(d) The principal limitations in the reduction of substation sizes by means of automatic and remote control are (1) investment, (2) substation losses, (3) substation maintenance. In cities these factors may be increased only within very narrow limits without increasing the total cost of power. In such cities as Cleveland, it is doubtful if the capacity of substations can be profitably reduced below 3000 kw. with the control equipments now available for full automatic control, commencing at the incoming supply line and extending throughout the entire substation operation. It has been repeatedly pointed out that to produce an efficient result, some form of remote control will probably be required in order to prevent an excessive amount of starting and stopping and the consequent loss in efficiency. Within the range of substation sizes considered in this paper for metropolitan systems (6000 kw. to 1500 kw.) the variation in total cost of power per mile of double track is small. There are, of course, some distinct advantages to be had by installing small capacity substations of say less than 3000 kw. These are principally the mitigation of electrolysis, and under certain conditions an increased factor of safety. Measures for the mitigation of electrolysis are receiving more and more attention. In a large substation having several units, trouble in one machine at peak load may result in failure of the entire station, whereas, if this capacity be separated by several thousand feet of feeder copper, trouble on a machine of one substation is much less apt to be transmitted to another machine in the adjacent substation, since the connecting circuit serves to damp out the surge.

The fact that the 3000-kw automatic substation in the examples cited apparently effects very little if any saving in the total cost of power as compared with the 4500 kw. or 6000 kw. manually controlled substations, is due to the increase in investment, substation losses, and increased maintenance, which just offset the savings in the cost of distribution. If, therefore, any substantial saving in the total cost of power is to be had by the smaller sizes of substations, automatically controlled, it will be necessary to reduce substation losses by improving methods of control. In the opinion of the writers, this should not be done by imposing upon a full automatic control substation additional remote control appliances. The complexity of such an arrangement is extremely undesirable. It is proposed that this result may perhaps be best secured by providing the simplest form of semi-automatic control substation, comprising a transmission line directly and permanently connected to the substation transformer primary circuit, and a synchronous converter arranged to start automatically from the transformer secondary circuit when the same is energized. This simplified semi-automatic control substation is absolutely under the manual control of the operator at the supply station and if the capacity of the substation be determined with regard to the economical capacity of the high-tension supply line, it may well be a single-unit station. On the other hand, if the reduction in capacity is carried to a point beyond this, a further division of a substation into smaller sizes may be had by grouping two such smaller substations on one economical supply line. Provided this method of control can be developed in a practical way, and there appear to be no serious obstacles, then there should result a substantial saving in the cost of power for substation sizes under 3000 kw. with the consequent advantages in the mitigation of stray currents and additional factor of safety as previously pointed out.

(e) Inasmuch as even a small difference in substation maintenance cost may be the deciding factor in a comparison between two distribution layouts, the standardization of substation equipment with the resultant economies is a matter of importance. While in some cases it may, at first thought, be desirable to use large units in the congested districts of a city and much smaller units in the outlying districts, it is quite possible that such an apparent advantage may be offset by an increase in maintenance expenses. The mechanism of the automatic substation is exceedingly complex and it is necessary to keep on hand a very large variety of spare parts, the investment in which is no small factor. If it be possible to adopt a standard size of unit and a standard control layout to be used in all substations, there will be an appreciable saving in the investment for spare parts. Furthermore, it is probable that maintenance labor may be reduced by such standardization. It is difficult to find and train good maintenance men and this difficulty would be substantially increased by the use of machines of various sizes and different control layouts.

Inasmuch as the heating losses in return circuits increase as the square of the current, it is apparent that smaller distances in the congested districts of a city and the consequently smaller track currents, are justified. If a substation of standard size be adopted, it would, of course, be necessary to space substations at smaller intervals in the congested districts than in the outlying districts. Other things being equal, this would be quite proper for the reason set forth above.

Appendix I

In equation (1) for total annual cost for type (a) feeder the heating loss is

$$I^2 \left(\frac{D \rho}{m} \right)$$

but for the type (b) feeder in which the load is uniformly distributed, heating loss is

$$I^2/3 \left(\frac{D \rho}{m} \right),$$

or

$$(0.577\, I)^2 \frac{D \rho}{m}$$

since

$$i = \frac{I x}{D}$$

where x is the distance from end or neutral point to any point on feeder and

$$\text{heating loss} = I^2 \int_0^D x^2/D^2 \rho \frac{d x}{m}$$

$$= I^2/3\left(\frac{D\,\rho}{m}\right)$$

Appendix II

$$i = \frac{I\,x}{D}$$

$$m_x = \frac{m\,x}{D}$$

$$\text{loss} = \int_0^D i^2\rho\frac{d\,x}{m_x} = \frac{\rho\,I^2\,D}{m\,D^2}\int_0^D x^2/x\,d\,x$$

$$= \frac{I^2}{2}\,\frac{D\,\rho}{m}$$

Appendix III

Type (*b*) feeder.

$$m = 0.577\,I\sqrt{\frac{2820\,p + 24.7\times 10^6\,L\,e}{f}}$$

$$= 30.64\,I\sqrt{\frac{(p + 8760\,L\,e)}{f}}$$

$$H_b = 0.001\,\frac{I^2}{3}\times D\left(\frac{10.35}{m} + G\right)$$

Let P = power per foot of track actually used by the cars during the peak.

Let V = substation bus voltage.

$$P\,D + H_b = \frac{I\,V}{1000}$$

$$H_b = 0.001\,\frac{I^2}{3}$$

$$\times D\left\{\frac{10.35}{30.64\,I\sqrt{\frac{(p + 8760\,L\,e)}{f}}} + G\right\}$$

$$= \frac{0.000112598\,I\,D}{\sqrt{\frac{p + 8760\,L\,e}{f}}} + \frac{0.001}{3}\,I^2\,D\,G$$

$$D\left\{1000\,\frac{P}{I\,V} + \frac{0.112598}{\sqrt{\frac{p + 8760\,L\,e}{f}}} + \frac{I\,G}{3\,V}\right\} = 1$$

$$D = \left\{\frac{V}{\frac{1000\,P}{I} + \frac{0.112598}{\sqrt{\frac{p + 8760\,L\,e}{f}}} + \frac{I\,G}{3}}\right\}$$

EXAMPLE:

Let V = 600 volts

P = 130 kw. per mile or 0.0246 kw. per foot

Load factor = 0.40

$G = 2.5 \times 10^{-4}$ ohm per foot

f = \$0.0186

p = \$24.00 $\quad p + 8760\,L\,e = 41.52$

$$\left.\begin{aligned} e &= 0.008 \\ L &= 0.25 \end{aligned}\right\}\; L\,e = 0.002$$

$$\sqrt{\frac{p + 8760\,L\,e}{f}} = 47.25$$

I	D	$P \times D$	Used by Cars Kw-hr. per yr.
600	13,670 ft.	337	1,183,000
400	9,350 "	230	808,000
200	4,780 "	118	414,000
100	2,410 "	59.4	208,500

ANNUAL COSTS

	Power Used by Cars		Distribution		
	Carrying Chg.	Oper. Ex.	Feed	Rail & Ground	Total
600	8088	9464	1625	+ 160	19,337.00
400	5520	6464	740	+ 52	12,776.00
200	2832	3312	189	+ 6.60	6,339.00
100	1426	1668	47.60	+ 0.80	3,142.40

Multiply total cost by 5280/D for cost per mile.

7470

7220 $\quad D = 0$

7000 $\quad$ Cost = \$6764

6895

Discussion

V. E. Thelin: The manually operated substations now in operation on railway systems in large cities offer a wonderful field for the use of automatic equipment, due to the fact that the line losses can be reduced considerably, schedule speeds increased, and in many cases sufficient copper can be taken down to pay for the cost of the land and new buildings as well as that of moving the machines. If the manually operated substations, which have a capacity of from 4000 to 20,000 kw., are redistributed into any number of single-unit or, at the most, two-unit automatically controlled substations, the service rendered by same no doubt will be far superior to that now obtained in the manually operated substations, due to the fact that each operation in the automatic substation has been worked out beforehand and the entire sequence is carried through without any hesitancy or error such as frequently happens to the operator in manually controlled stations. In the large manually operated substations with many units it is necessary to clear the board of practically all the feeder sections before the first rotary can be connected to the bus, whereas a single-unit automatic substation will have a maximum of say from five to eight feeders, and there should be no difficulty experienced in the station picking up all the sections simultaneously. It is possible, through the use of special devices which I have in mind, to isolate each substation district from all other districts, and by using automatic reclosing circuit breakers service can be restored quickly, whereas if all substations were tied together through bus lines the first station to be connected to the system would open up an overload through excess of load fed from the surrounding substation districts through the bus lines.

It seems, for many reasons, that the ideal automatic substation layout in a large metropolitan city is the single-unit substation layout. A two-unit substation requires the use of high-tension line oil switches, rotary oil switches and transfer switches, together with the expensive bus bar compartment construction for line busses, transfer busses and rotary busses, and where compound rotaries are used equalizer busses must be used, and the automatic control for a multiple-unit substation becomes very complicated, due to the fact that arrangements must be made for one rotary to carry the load in the light portions of the day and for additional rotaries to be brought into service as the load increases. Also, if trouble is experienced in the operation of one rotary, the automatic equipment must be so arranged as to cut in one or more rotaries, and the remaining rotary or rotaries are therefore called upon to carry the load which was originally carried by all of the rotaries originally in service in the station, which fact results in the remaining rotary or rotaries, as the case may be, being subject to an overload. On the other hand a single-unit substation can be constructed very economically, due to the fact that it is necessary to put in one oil switch only, which acts both as line and rotary switch, and which eliminates practically all of the expensive high-tension bus bar construction. By using one rotary, only, in the substation it is possible to put a 1000, a 2000, or even a 4000 kw. rotary in a building of simple construction on a 25-ft. lot. In case an oil cooled transformer is used, it is not necessary to build a basement in the substation, the cables being run in ducts under the floor and the rotary being set on a foundation with a pit in same, in order to get under the rotary for necessary repairs, etc. If air blast transformers are used, such as is now the case in a great many of the present hand-operated railway substations, the oil switch and transformers can be placed over a small basement-like compartment, which compartment would only have to be big enough for a man to enter to make the necessary repairs. The blower for cooling purposes is connected directly to this basement.

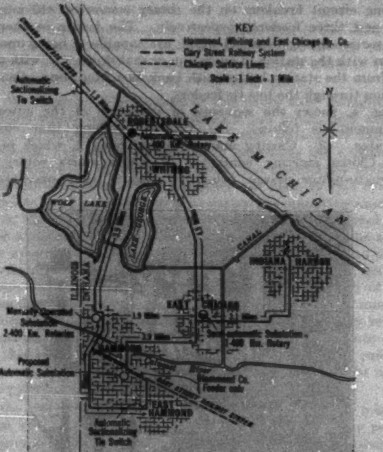
KEY
Hammond, Whiting and East Chicago Ry. Co.
Gary Street Railway System
Chicago Surface Lines
Scale : 1 Inch = 1 Mile
N
LAKE MICHIGAN
Automatic Sectionalizing Tie Switch
1.1 Miles
ROBERTSDALE
Automatic Substation 1-400 Kw. Rotary
WHITING
WOLF LAKE
LAKE GEORGE
1.9 Miles
CANAL
INDIANA HARBOR
ILLINOIS
INDIANA
Manually Operated Substation 2-400 Kw. Rotaries
1.9 Miles
EAST CHICAGO
3.1 Miles
2.9 Miles
Semi-automatic Substation 1-400 Kw. Rotary
HAMMOND
Proposed Automatic Substation
River
Hammond Co. Feeder cuts
GARY STREET RAILWAY SYSTEM
EAST HAMMOND
Automatic Sectionalizing Tie Switch

FIG. 1—HAMMOND, WHITING AND EAST CHICAGO RY. CO. SYSTEM

I do not agree with the authors of the paper in their statement that a 3000 kw. unit is the minimum size which can be economically installed in city service, as I feel that with single-unit substations and simplified type of automatic control equipment it is possible to economically install substations with as low as 1000 kw. capacity.

The following figures might be of interest in connection with the application of automatic substations in city service. Fig. 1, shows the present layout of the Hammond, Whiting & East Chicago Ry. system. This system, which operates approximately 30 miles of track, originally was fed from one manually operated substation located in Hammond, which station contained four 400-kw. rotaries. In order to improve operating conditions, one of these rotaries was moved to East Chicago and equipped with various protective devices, which prevent any damage occurring in case of trouble arising due to hot bearings, over-speed, reverse current, etc. The feeders and the rotary are protected by means of automatic reclosing circuit breakers. The station is started in the morning by an inspector and left to run by itself all day, being shut down at night by means of a clock, which first trips out the circuit breaker and then opens the oil switch. This substation has been in operation as a semi-automatic station for approximately four and one half years, and has given very satisfactory results in normal operation. Shortly after this station was put in service another station was built at the north end of the system, viz. at Robertsdale. The power supplied to these three substations is furnished, however, from the same high-tension line, and after any interruption on this line it was necessary to carry the load on the two rotaries in the manually operated substation in Hammond until the inspector was able to get over and start the East Chicago substation, after which the Robertsdale substation was started. Having had some experience as a substation operator, I felt that a simplified automatic substation control equipment, with fewer parts than had been used heretofore in any automatic substation, could be

FIG. 2—AUTOMATIC CONTROL PANEL

developed, which would do electrically exactly what an operator does manually when starting a substation. After various tests and experiments such an equipment was developed, and has been in daily operation for approximately two years, having given very satisfactory results.

Fig. 3

Fig. 2 shows the details of the automatic control panel in this station, as follows:

Directly below the time clock which starts the operation of the station is a master relay which energizes the various circuits in the station. Below that is a polarized relay, which determines whether or not the balance of the operation should be carried through or whether the polarity of the rotary should be corrected in case it came up wrong. Beneath the polarized relay is a combination field control and change-over switch, which, in addition to changing the connection of the field from the station bus to the rotary itself, also performs various other operations either simultaneously or with a certain time relay. The various protective devices shown at the top of the panel protect the rotary from all possible cases of trouble that may arise, such as reverse phase, phase failure, reverse current, over-speed, etc. The switches at the bottom of the panel are used for the purpose of cutting out the automatic equipment and reconnecting the balance of the equipment in such a way as to enable the substation to be operated as a semi-automatic in case any of the various automatic devices are out of order.

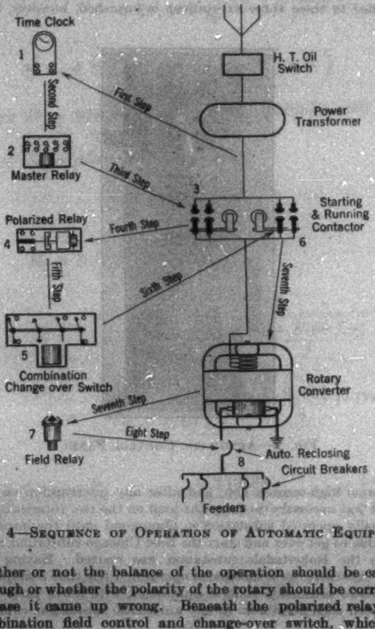

Fig. 4—Sequence of Operation of Automatic Equipment

Fig. 3, shows, reading from left to right, the automatic reclosing circuit breakers on the rotary converter, the auxiliary bus and three feeders, respectively. The feeder breakers are bus sectionalizing breakers which are capable of being operated either with the station in operation or shut down, *i. e.* with power fed from the station bus or with back feed from some other substation through the bus tie feeders.

Fig. 4, shows the sequence of operation of the automatic equipment as follows: (1) Contact making time clock 1 operates. (2) Closing master control relay 2, which in turn (3) Closes starting contactor 3, which starts rotary. (4) Magneto-motor driven polarized relay 4, then operates, (5) Closing combination feed control and automatic change-over switch 5, which in turn (6) Opens starting contactor 3 and closes running contactor 6, (7) After which field-circuit time-limit relay 7 closes and, (8) Automatic reclosing circuit breaker 8 on machine panel closes, picking up station load. All of which operations require approximately 25 seconds.

Fig. 5

In case the station comes up with reversed polarity, polarized relay 4 shuts the stations down, after which the rotary starts again and operations 1, 2 and 3, shown above, are repeated until the rotary comes up positive, after which the regular sequence of operation is carried through. This condition, however, will rarely occur, due to the fact that the field of the rotary is excited with one-tenth full strength field from the station bus during the time that the rotary converter is being started up, which causes the field to come up with correct polarity. Out of approximately 500 tests that were made with the field connected to the bus in this manner, there was only one case noted where the rotary converter came up negative, which possibly might have been caused by poor contact of some of the fingers, etc.

The equipment is so designed that each operation in the sequence is a function of the one preceding it, *i. e.* each operation must be carried through successfully before the next one can take place. It is also so designed that if the d-c. automatic reclosing machine circuit breaker does not close and pick up the station load within a certain predetermined time after master relay 2 has closed, the self-correcting relay shown to the left of the time clock will then trip out the master relay, which in turn shuts down the rotary. The rotary then starts up again and if the trouble was caused by an imperfect contact or the sticking of some interlock, it may operate perfectly now and the entire sequence of operation is carried through, and the station load is picked up.

Fig. 5, shows, reading from left to right, the starting and running contactors for the automatic equipment; the manually operated starting and running switch; and, at the extreme right, the a-c. oil switch control panel.

The only other equipment in the station that is not shown in any of the accompanying photographs is that of the rotary converter, which I did not consider it was worth while to show, inasmuch as it does not show any new equipment.

D. W. Roper: The authors of this paper have brought out one point which cannot be emphasized too much, and that is that if the introduction of the automatic station for railway distribution will provide a method of increasing the number of feeding points for the railway system, the electrolysis problem will largely disappear. The tendency has been to put in substations as large as possible so as to reduce the operating expense, that is, the expense of the substation operators, and that has served to make the feeding distances very long. With the automatic substation the tendency is in the other direction, to make the substations comparatively small, and in this way greatly increase the number of feeding points. As the length of the feeders diminishes very rapidly with the increase in the number of substations, so also does the length which the railway return current travels the rails reduce in the same way: and not only does this affect a reduction in the voltage drop in the railway return circuit, but also effects a material reduction in the losses in the return circuit.

If the operators of the railway systems in planning the rehabilitation which they are looking forward to, after the long period of depression—would install as many substations as economically possible, and in this way reduce their feeding distances, it will very materially reduce the complaints and the damage which have heretofore been caused by electrolysis.

W. E. Bryan: The subject of economics of railway distribution, especially in view of the advent of the automatic substation, merits the most careful study by the electric railway engineer. The economic side of this question has been too often neglected in the past, due in large measure to the fact that railway systems have grown through the process of consolidation and ideal distribution layouts were, therefore, difficult of attainment. The automatic substation has interjected an important element into the field and railway engineers must be prepared to take full advantage of this new development which means some readjustment of our previous ideas as to size of stations, type of buildings, etc.

As the writer has pointed out previously, variation in local conditions makes general conclusions applicable to cities of a given size not only difficult of determination, but of doubtful value as well. Not only must conditions in any particular city be studied as a problem by itself, but a solution applicable to one section of a city may not be the best solution for another section, due to variation in the cost of land, availability of conduit, etc. Another point which has an important bearing is the question of power supply. In St. Louis, for instance, the railways receive power from three sources, namely, purchased water power at 55 per cent load factor; purchased steam power at 40 per cent load factor and power generated in its own plants at 14 per cent load factor. St. Louis has several d-c. feeders which are admittedly poorly designed from a distribution standpoint, but which, nevertheless, considering the different costs of the various sources of power, provide the best arrangement from an economic standpoint.

The authors on page 363 derive a figure for the cost of distribution amounting to $250,000 per year which they state is fairly representative of cities of the size of Cleveland. As the figures in this tabulation are used more or less throughout the paper, the writer has drawn up comparable figures for St. Louis which indicate that the annual cost of distribution in that city amounts to approximately $505,000 per year. It should be stated that the investment data used is based on conservative valuation figures recently prepared for presentation in a case before the State Public Service Commission, and corrected as of April, 1922. Incidentally, it might be brought out at this point that the larger the distribution loss, the greater the possible saving which can be effected by the use of an increased number of substations. In other words, if as the authors conclude, stations of 3000-kw. capacity are best adapted for cities where the annual distribution cost is $250,000 per year, it seems logical that if the distribution loss is considerably in excess of this figure a greater number of stations and, therefore, stations of smaller capacity are justified.

In view of the wide difference in the annual costs of distributions just referred to, a brief explanation of how the writer's figure of $505,000 was obtained is in order. The carrying charges on feeder investment are found to be $135,000 as compared with the figure of $130,000 used in the paper. The writer's figure represents a 10 per cent charge on a valuation of $1,350,000 for positive and negative distribution circuits. In view of the low depreciation of copper the writer considers 10 per cent preferable to the 13 per cent fixed charge rate used by the authors.

The principal variation, however, comes in the second item, namely, the carrying charges on that portion of the investment in generating plant, transmission lines and substation equipment necessary for supplying the peak load distribution losses. The writer's figure is $240,000 as compared with the figure $92,000 derived in the paper. This difference is due to two factors; first, an increase in the cost of investment per kilowatt of direct-current demand from $165 to $258: second, the distribution losses during the peak, based on many readings taken at various points scattered throughout the city, was found to be for St. Louis practically 15 per cent as compared with 10 per cent as used in the paper.

Returning to the first item just mentioned, namely, the investment per kw. in generating plant, transmission lines and substation equipment, it is important to bear in mind that this figure is based on the d-c. demand at the substation bus. With a coincident half-hour average d-c. demand of 45,000 kw. (the figure for St. Louis), the demand at the generating bus amounts to 53,000 kw., the average loss at the time of peak load for transmission and conversion amounting to 15 per cent. If it is assumed that the generating plant should have a reserve capacity of 25 per cent and that its present day cost would amount to $125 per kw. of capacity (which is considered by the writer a very conservative figure), the investment cost in generating plant reduced to the basis of d-c. demand amounts to $183 per kw. The addition for transmission cable, underground conduit and substations brings the total to $258 per kw. It would seem that the figure used by the authors, namely, $165, is considerably lower than could be realized in practise, especially in view of the statement at the bottom of page 367 of the paper, that generating plant investment alone might be as high as $150 per kw.

This factor, that is, fixed charges on investment necessary to supply peak load losses, is the most important of the three factors entering into distribution costs and if automatic stations, especially in congested districts are properly adjusted as to voltage, a very material saving in the item will result due to the saving in distribution losses.

For the third item entering into the cost of distribution, namely, operating expenses of generating plant, transmission lines and substations necessary to supply distribution losses, the writer obtains $130,000 per year as compared with $28,000 given in the paper. Although the same "Loss Factor" is used, the writer has applied it to the peak load loss, multiplying the resulting figure by 8760, and not to the annual kw-hr. output, as was inadvertantly done by the authors. The difference is further increased by the use of 15 per cent distribution loss on the peak instead of 10 per cent, and to a slightly higher energy charge for power.

A comparison is given on pages 374 and 375 of the use of stations of various sizes ranging from 1500 to 6000 kw. Messrs. Crecelius and Phillips have determined the probable distribution distance for each of the stations considered and have worked the problem out on this basis. The railway engineer is usually confronted with the necessity of taking care of a given district and the question to be determined is whether the district shall be fed by one, two or perhaps more stations. This would seem to be, therefore, the more logical basis of comparison, and in his comments on the conclusions presented in the paper the writer will give actual figures derived from the downtown section of St. Louis. In passing, however, it might be pointed out that the investment costs of the 3000-kw. station and the two 1500-kw. stations used by the authors are $43 and $53 per kw. respectively. A comparison of a 2000-kw., two-unit station and two 1000-kw. stations for St. Louis resulted in investment costs of $38.25 per kw. for the former and $39.75 per kw. for the latter. These figures are based on the actual purchase price of equipment recently bought by the United Railways and estimated costs for land and buildings, these latter, however, being obtained from figures for land actually purchased for substation sites and buildings recently built for two automatic substations now in service. In explanation it might be pointed out that the cost of the control equipment for the two-unit station is, as might be expected, slightly higher than the cost at the two single-unit stations, due to the additional control devices necessary in a two-unit station. This difference is more than offset, however, by the increased cost of land and buildings for the single-unit stations, but as we have been able in St. Louis to secure inexpensive land (rear portions of lots, etc.) and erect simple and inexpensive buildings, these factors are not of great importance. The writer wishes to stress the point, however, that the maximum advantage of automatic stations can only be obtained where land and building costs are held to a minimum. Automatic equipment lends itself to simple and inexpensive types of buildings.

In the operating costs derived by the authors for 3000-kw. and 1500-kw. stations, the larger station is given a material advantage in efficiency. This point will be covered later, but it is evident that if the efficiencies were practically the same there would be little advantage from an economic standpoint in favor of the 3000-kw. station. What advantage remains would be more than offset by increased freedom from electrolysis and greater reliability, advantages which are brought out in the paper.

Commenting on paragraph (b) of the conclusions (page 376), the writer cannot agree that, "in cities . . . the economic advantages of the automatic substation are relatively small, because distribution cost is a correspondingly small part of total cost." As shown previously, distribution costs are a material item in the cost of supplying power to a railway and the automatic station undoubtedly has a large field in urban work. Further study and experience is necessary before the question of its relative value for interurban, as compared with urban service, can be definitely answered.

In paragraph (c) the authors conclude that in view of the lower efficiency which they say is to be expected with automatic stations, some plan of remote control will probably be found advisable, so that converters can be operated at or near their best efficiency. This conclusion evidently is based on the efficiency curves of 60-cycle converters which constitute a minor portion of the converters in use on railway systems. Efficiency curves of the 25-cycle converters differ from those of 60-cycle converters in two important respects. First, very little increase in efficiency is obtained as the size of the unit is increased above 1000 kw.; and second, the variation in efficiency from three-quarters to one and one-fourth load in the case of 25-cycle units is about ¼ of one per cent. These figures are based on the combined efficiency of converter and transformers. Manifestly, it is of comparatively little importance at what point the unit is operated, provided it is above three-quarters load. Even at half load the efficiency of a 25-cycle 1000-kw. converter and transformer is only ¾ of one per cent, less than its maximum. The curves on page 370 of the paper giving the efficiencies of 60-cycle units at various loads show that the efficiency of a 1000-kw. unit at 50 per cent is 2¼ per cent rating less than its efficiency at full-load rating.

In St. Louis the five new automatic stations recently purchased are laid out to carry approximately 125 per cent of rating for the maximum half hour which would result in an average load of about two-thirds of rating. The relays will be set so that the stations will run practically continuously for sixteen to eighteen hours per day, the slight loss in station efficiency at the lighter loads being more than offset by the saving in distribution losses. The stations and feeders are so designed that if one station is out of service the overload on adjacent stations will not reach the danger point, nor will the distribution voltage be seriously affected. It should be remembered that such equipment is capable of 50 per cent overload for two hours and, furthermore, the stations being small and comparatively close together, prolonged overload at any one station is very unlikely.

In connection with the conclusion set forth in paragraph (d), namely, "in such cities as Cleveland, it is doubtful if the capacity of substations can be profitably reduced below 3000 kw., . . . ," the writer cites the following: In St. Louis it was desired to reduce the load on a 12,000-kw. substation feeding principally the heart of the downtown section. It was decided to move two 2000-kw. interpole rotaries from their locations in existing stations into the downtown district fed by the 12,000-kw. station. Three alternatives for the use of this equipment presented themselves. First, a single 4000-kw. station manually operated; second, a single 4000-kw. station automatically operated, and third, two 2000-kw. stations automatically operated, spaced approximately 4500 ft. apart. Without going into detail, (the writer will be glad to furnish the detailed figures upon request) the following figures represent the annual costs, based on the investment necessary for *additional* equipment, and land, buildings, transmission cables, distribution cables, together with allowance for distribution losses: 4000-kw. station manually operated, $14,250; 4000-kw. station automatically operated, $13,800; 2-2000-kw. stations automatically operated, $13,000. In view of these figures, together with the greater freedom from electrolysis and increased reliability, it was decided to adopt the plan involving two 2000-kw. stations automatically controlled, and equipment has been purchased and land for these stations acquired. Each station is supplied by two transmission cables.

In view of the figures just given the writer feels that for cities similar to St. Louis, the 3000-kw. station is not the minimum size justifiable. Furthermore, if automatic stations of 2000 kw. can be justified in a congested downtown district, where the feeding distances are comparatively short, it seems evident that in districts outside of the downtown area, where conditions more nearly approach interurban conditions, the automatic station of smaller size, say 1000 kw., finds a useful field. It is not contended that in areas like the loop district of Chicago, where concentration of load is extremely heavy, that automatically controlled equipment will be found advisable.

The conclusion expressed in paragraph (e) that if possible, standard size of unit and standard control layout be used in all stations, is open to the objection that if units of one size are used exclusively, the maximum distribution economics cannot be obtained. Division between various sizes, of course, should not be carried to too fine a point, but it would seem that for a city the size of St. Louis, 1000-kw. units would be best for general use, with 2000-kw. units for the downtown district and other points of heavy load concentration, and say 500-kw. units for use at outlying points and on interurban lines. Such a plan will not, it is believed, materially increase the necessary stock of spare parts, since many items of the control equipment are the same for various size units.

Relative to adopting a standard control layout, while this plan has material advantages, it also has certain commercial disadvantages and, furthermore, it should be borne in mind that we can expect to see changes of a more or less radical nature in automatic control equipment as the art develops.

M. J. Lowenberg: In the design of a distribution system, whether it is for a small railway system or a heavy electrification, it is necessary to determine the permissible voltage drop. Often, especially today when capital costs have to be kept down, irrespective of any economy that theory may show according to Kelvin's law, that value is the minimum value to operate the trains or cars.

A very simple law is that for the most economic layout the cross section at any point should be proportional to the square root of the current at that point.

I have found from computations checked by tests, that whether it is a single car or a long train, or a number of cars or a number of trains, that a very accurate method is to assume that this current at any point (to which the cross section is proportionate to its square root), is the maximum starting current of any single unit—(which in a street railway would be a car and in a subway would be a train)—plus the current due to average load uniformly distributed along the line.

In using Kelvin's law great care must be taken not to throw an undue burden upon the stockholders. Kelvin's law is subject to a tremendous variation, without changing the economy derived from theory. As a matter of fact, 35 per cent less copper than shown by Kelvin's law would in theory give approximately only 10 per cent increase in annual cost, and if you put the question to a banker he would tell you to leave out the 35 per cent copper.

Another point in the paper which is not entirely in agreement with practise is the variation of the size of cables. In most systems, especially large systems, there is more or less standardization—especially on underground work. There you must standardize on a certain sized cable, irrespective of what your theory shows. These things will often upset Kelvin's law, to which too much weight must not be given.

The extent of spare equipment, whether feeders, substations or rotaries, must be determined in co-operation with the transportation department; for then only can you determine the value of service and therefore the amount of relay equipment which has to be installed.

E. R. Shepard: The paper is of particular interest to me because of its possible bearing on the question of electrolysis. If, through, the use of semi-automatic or remotely controlled substations, the feeding capacity at any one point in a city system can economically be reduced to from 1500 to 3000 kw. we may find in such systems a final and satisfactory solution for this baffling problem. That such will be the case is by no means a foregone conclusion as the establishment of numerous substations throughout a city will create new positive conditions on the underground structures which in some soils may prove injurious.

The application of insulated negative feeders for the mitigation of electrolysis, while improving the general conditions, have in a number of instances created new positive areas with consequent damage to pipes and cables.

Where relatively few and large generating or supply stations are in use they are frequently located outside of the congested or highly developed sections of cities, and in such cases electrolysis conditions are often either endured or taken care of by local treatment. With the use of frequent automatic substations, some would usually be located in congested areas where the underground utilities are not only of great value but where the interruption of service or the failure of water pressure cannot be threatened.

The use of additional supply points for power distribution is, of course, in the right direction to eliminate electrolysis, and I am not unmindful of the great benefits which may be derived from carrying such a system to the economic limit. It is not evident, however, to what extent such a system will remove the cause of electrolysis and the railways may well assume that they will have this problem with them until direct current has been supplanted by some other form of motive power.

L. P. Crecelius and V. D. Phillips: Mr. Thelin has said "I do not agree with the authors of the paper in their statement that a 3000-kw. unit is the minimum size which can be economically installed in city service, as I feel that with single-unit substations and simplified type of automatic control equipment it is possible to economically install substations with as low as 1000-kw. capacity."

The authors agree with Mr. Thelin that some simplified form of control may justify the installation of substations of less than 3000 kw. capacity. To correct any wrong impression that may have been created as to the opinions expressed by the authors, it may be well to quote from conclusion (d) of the paper. "In such cities as Cleveland, it is doubtful if the capacity of substations can be profitably reduced below 3000 kw. with the *control equipment now available for full automatic control*, commencing at the incoming supply line and extending throughout the entire substation operation" * * * * * "If, therefore, any *substantial saving* in the total cost of power is to be had by the smaller sizes of substations, automatically controlled, it will be necessary to reduce substation losses by improving methods of control" * * * * "There are, of course, some distinct advantages to be had by installing small capacity substations of say less than 3000 kw. These are principally the mitigation of electrolysis, and under certain conditions an increased factor of safety."

It would appear that Mr. Bryan has not correctly interpreted the mathematical procedure and examples upon which the authors have based their conclusions, with which conclusions Mr. Bryan is not altogether in accord. Mr. Bryan refers to the tabulation given on the first page of the paper as being "used more or less throughout the paper." It should perhaps be pointed out that this tabulation was given simply for the purpose of illustrating in a general way the magnitude of the several elements which go to make up the total cost of distribution. These figures are not used or referred to again in the body of the paper.

Mr. Bryan has preferred to use 10 per cent in arriving at the carrying charges on copper. This is, of course, a matter of opinion. The authors arrived at 13 per cent by using an 8 per cent return on the investment, which percentage has been quite generally allowed throughout the country by the state public utility commissions; 2½ per cent for taxes, which is the tax rate in Cleveland and which in view of steadily increasing tax rates throughout the country is not believed to be excessive; and 2½ per cent for depreciation. It is true that depreciation on the copper itself is very slight, but it must be remembered that the rate applied to the cable in place must take account of the rather rapid depreciation of insulation and cost of stringing. It is believed that in a comparative study of this kind, depreciation of feeder insulators and fixtures need not be included for the reason that this investment is practically the same for different sizes of feeder. If these items be included the result will not be substantially affected.

With regard to the amounts used by Mr. Bryan for generating plant, transmission line, and substation investment, it may be said that the unit values used will depend upon the basis of valuation. There is a wide difference of opinion among rate making bodies as to the weight that should be given to the high prices prevailing during the last few years, especially in appraising for rate making purposes such plants as were installed prior to 1915. On the basis of present day costs Mr. Bryan's figure of $258.00 per kw. is undoubtedly more nearly correct than the figure of $165.00 used by the authors. At the same time, the figure of $165.00 is quite consistent with the valuations used by a number of different public utility commissions in determining rates. The present tendency is toward the purchase of power from central stations by electric railway companies. On account of the diversity of load on these stations the investment properly allocable to a single consumer or class of consumers is substantially reduced. The demand charges for purchased power in the larger cities range from as low as $12.00 up to $27.00 per kw. of demand per year. The figures used on the first page for these carrying charges, viz: $23.00 per d-c. kw. of demand per year, including carrying charges on substation investment and taking due account of the substation losses, is believed to be reasonably consistent with the demand charges mentioned above, as well as consistent with the valuations on power plants and transmission lines accepted by many rate making bodies.

In the opinion of the authors, Mr. Bryan's discussion of the paper presents figures and observations of no little interest and value. Mr. Bryan touches upon a number of points that must certainly receive due consideration in any study of the problem of distribution.

Mr. Lowenberg's statement that "Kelvin's law is subject to tremendous variation without changing the economy derived from theory" is, in the main, true. In other words, the cost curve is fairly flat on either side of the point of maximum economy. It must, however, be borne in mind that the load on feeders in most progressive American cities is continually growing, for which reason it may prove wise to install more than the minimum copper as contemplated by Mr. Lowenberg. The application of Kelvin's law in cities gives substantially more copper than is necessary to satisfactorily operate cars. On the other hand, in the case of interurban lines on which distribution distances are necessarily much greater, Kelvin's law will call for little, if any, more copper than will generally be necessary to obtain satisfactory car operation. The authors certainly did not contemplate such strict application of the law of economy as to depart from that "more or less standardization" of cable sizes to which Mr. Lowenberg refers. Very few theoretical engineering laws of this sort can be precisely applied in practise. Kelvin's law gives the theoretically proper sizes of cable corresponding to maximum economy in distribution. In other words, it affords a standard of performance to be approached as nearly as may be practicable, but which of necessity must be modified in many cases by reason of various practical considerations. Mr. Lowenberg points out that it may be difficult or unwise to invest more than the minimum of capital necessary to conduct transportation. This is, of course, a matter of financial policy rather than engineering computation. It is one of those practical limiting conditions referred to above.

Mr. Roper and Mr. Shepard have referred to the mitigation of the electrolysis difficulty by the installation of a larger number of distributing points. In their analysis, the authors have not specifically considered the savings that may result from the use of a large number of small substations in cutting down electrolysis damage claims or in reducing the necessity and cost of various mitigative measures. This omission must not be interpreted as indicating any lack of appreciation on the part of the authors as to the importance of this phase of the subject. It is scarcely possible, however, in an analysis of this kind to introduce the factor of electrolysis because of the tremendous variation in local conditions governing corrosion from stray currents. The examples worked out in the paper for a typical mile of track show a rather small variation in total cost for the several different substation sizes. It may frequently happen that a serious electrolysis situation will justify the use of smaller substations than would be dictated by the other purely economic factors.

In conclusion, the authors wish to say that their primary purpose in preparing this paper has been to set up a procedure for the study of the distribution problem in a comprehensive way. The various examples which have been worked out have been intended more for the purpose of illustrating the application of the principles involved than for the purpose of reaching any very definite conclusions. Railway substation control is still in process of development. There is a great variation in the many factors which go to determine the proper solution of the distribution problem in different localities. As previously pointed out, questions of financial and operating policy, including the importance attached to continuity of service and the resultant provisions that may be necessary to reduce the possibility of shut down, must be given consideration along with the theoretical economic factors. At the same time, it is believed that the starting point at least is a purely economic analysis along such lines as have been suggested in this paper.

Light Without Glare

BY WARD HARRISON

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The object of this paper is to show what factors must be controlled in order to produce satisfactory illumination without glare.

The relative importance of brightness of light sources, their candle power, position in the field of view and contrast with the background are discussed. The paper includes tables from the Illuminating Engineering Society Code of Industrial Lighting in which for the first time various light sources, both natural and artificial are classified from the standpoint of glare. The use of these tables is explained and illustrative examples are given.

ARTIFICIAL lighting is an old art, so old in fact, that one's mental attitude toward it is influenced largely by tradition if not by heredity. How many there are who still judge the desirability of a lighting unit simply by its whiteness and dazzling power, criteria which served well in the days when vegetable oil lamps and tallow candles were the only light sources available and when perfect combustion, as evidenced by a brilliant white flame, was a phenomenon altogether too rare. There are many also in whose minds the thought of excessive heat is associated as the inseparable accompaniment of a high level of artificial illumination; they forget that the 200-candle power lamp of the present generates no more thermal units than did a single candle in the days of our forefathers. And as to the question of expense in lighting, it may be added that the cost per hour for the 200-candle power lamp is today only about equal to that of the aforementioned candle. In this connection, it is not without interest to take cognizance of the apparent anomaly, that, for some locations artificial light has actually become cheaper than natural light. For example, a number of our larger public buildings and even our art galleries have found it much more satisfactory and in the end less expensive to provide for the use of artificial light exclusively rather than to assume the high initial cost and the up-keep expense of large areas of exposed skylight.

It would be interesting also, to turn aside and see how modern developments have made it possible for our great industries to have daylight levels of illumination, and daylight quality of illumination, available throughout the twenty-four hours and ordinarily at the very moderate expenditure of from 1 per cent to 2 per cent of their labor cost. Just what this means, just what the difference is between 1 to 2 foot-candles, the old levels of artificial illumination and 10 to 20 foot-candles, the daylight level of interior lighting must be seen to be appreciated. One who has tested out for himself his acuity of vision and the difference in his speed of perception under these different levels of illumination has no difficulty in understanding why production invariably falls off with fading daylight in the great majority of our older and inadequately lighted industrial establishments; and how even a night shift in these same plants can be made profitable if proper lighting is supplied.

On the other hand, almost every one of the invaluable developments of modern applied science, such for example as the high-tension transmission of electric power, or the gasoline motor car, has brought its own particular hazards and a capacity for serious abuse. High power artificial light sources, or for that matter, modern prism glasses for the control of daylight, are no exceptions to this rule. Unfortunately, it is true that the potentialities of the newer lamps as aids to progress are only one-half utilized or appreciated and, by the same token, their flagrant abuses have for the most part been allowed to run along unchallenged. A typical machinist substitutes for his old stubby candle an unshielded incandescent lamp of 100 times its power and 1000 times its brilliancy; remarks, perchance, that it is such a fine light that it almost blinds him; and calmly goes on with his work for as many days as his eyes—or the law—will allow him.

Fig. 1—Glaring Light from Unshaded Local Lamp which is a Menace to Safety and to Vision

Now it is obvious that bare 100-watt lamps on drop cords will cause serious glare, that raising the lamp a foot or two above the direct line of vision, or perhaps enclosing it in a white diffusing globe will mitigate the harmful effect, but just what is the quantitative value of each of these factors, and just how far one must go to obtain reasonably satisfactory conditions for vision, are subjects regarding which there is still much lack of real information and of uniformity of opinion.

It is generally accepted that for a fixed position of light source the degree of glare experienced is a function of (a) brightness of the source—candle power per unit area; (b) total flux of light directed toward the eye from

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the source—candle power in the direction of the eye; and (c) contrast in brightness between the light source and its background. Authorities differ greatly as to the relative weights to be assigned to the three quantities and formerly (a) and (c) were particularly stressed. More recent investigations have, however, pointed toward the total flux of light which reaches the eye from a light source as being the most important single factor in the production of glare. The trend of present thought on this subject may be summarized in the form of four principal propositions as follows.

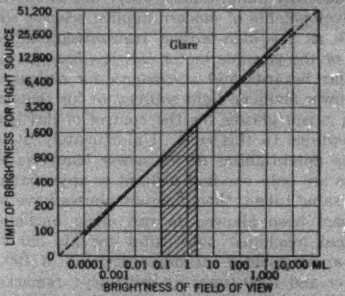

Fig. 2—Nutting's Data on Limits of Brightness

I. Dr. Nutting[1] found (see Fig. 2) that with a fixed area of light source at a fixed distance from the observer, increasing the brightness of the surroundings tenfold only permitted of approximately doubling the candle power (and brightness) of the source if no increased sensation of glare were to be experienced. In other words, the final contrast between the source and its background must be reduced to one fifth of its former value if it is desired to double the candle power of the source.

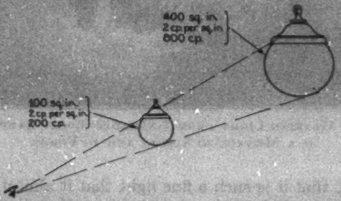

Fig. 3—Doubling the Distance between the Eye and Light Source Permits of Increasing the Candle Power Four Times

II. The results of other investigations[2] suggest that one may approximately double the candle power of a source having a fixed location if the area of that source is increased 10 times, which, of course, involves decreasing its brightness to one-fifth of the former value. It will be observed that in this case as in the preceding one, the resulting contrast between the source and its background is reduced to one-fifth in order to double the candle power of the source, without increasing the glare effect.

III. It is obvious from a consideration of Fig. 3, that if the brightness of the light source and the brightness of its background are both held constant and the distance between the eye and the source is doubled it will be permissible to quadruple the candle power of the source, since the brightness of the image on the retina will be the same in both cases and the diameter of the source is doubled to hold the area of the retinal image constant.

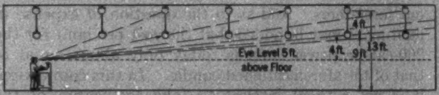

Fig. 4—Raising the Mounting Height of the Light Sources Well Above the Eye Level is the Greatest Single Factor in the Reduction of Glare

IV. If after doubling the distance between the eye and the light source and at the same time increasing the candle power and area four times to preserve the glare balance it is decided to cut in two the candle power of the source in this new position, it is then permitted by (II) to cut the area of the source to one-tenth and by cutting the candle power again in half the area may again be reduced to one-tenth so that with the candle power of the source the same as when in the first position close to the eye, the area of the source need only be 1/25 of that required by the first position. It may be said then that doubling the distance between the eye and a light source permits of dividing its area (and increasing its brightness) by 25.

These four illustrations should serve to make clear the major importance of candle power and distance from the eye, in a word "flux entering the eye", rather than the brightness or contrast as the dominant factors in glare. In truth, small bare incandescent lamps are under some circumstances really less obnoxious than frosted lamps of say five times the candle power used in the same location.

Formulas, in which these various relations are expressed algebraically are included in the Appendix. It should be borne in mind that the avoidance of glare is still far from being an exact science and the numerical values in these formulas may require very material revision as a result of later investigations.

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[1] P. G. Nutting, *Transactions I. E. S.*, Vol. XI p. 939.

Dr. Nutting's data show that if the candlepower of the source and the brightness of the background are both raised indefinitely, in this logarithmic ratio, a point is finally reached at which the brightness of the background is as great as that of the source. This point, which might be termed the glare limit, represents the brightest surface on which the eye can focus without immediate discomfort no matter what the surroundings. This brightness is approximately 50,000 millilamberts or about five times the brilliancy of white cardboard exposed to full sunlight.

[2] Ward Harrison, *Transactions I E. S.*, Vol XV p. 34.

As a specific application of these relations, assuming for the time their correctness, take the case of a lighting installation in a large office devoted to bookkeeping in which the lamps are suspended in glass diffusing globes four feet above the eye level (about nine feet above the floor) and in which the contrast between the units and the walls which form their background is found to be about 25 times too great for comfort. If no change is to be made in the size of the lamps the trouble can be remedied in any one of three ways.

(a) The brightness of the globes can be reduced to 1/25th of the former value by increasing the diameter of the globes five times.

(b) The brightness of the background can be increased 25 times by painting it a lighter tone and directing more flux toward it.

(c) In accordance with IV the units can be raised four ft. or to a height of eight ft. above the eye level (thirteen ft. above the floor—see Fig. 4).

Where the head room is sufficient this latter method certainly presents the easiest solution of the problem. In fact, the importance of locating interior lighting units well up toward the ceiling cannot be overemphasized. In street lighting, where, in nearly all cases the lamps are seen against an almost perfectly black background the need for high mounting is even more urgent.

Fig. 5—Specular Reflection or Glint may Sometimes Prove an Aid to Vision Especially in Street Lighting

The first comprehensive tabulation in which various light sources, both natural and artificial, are classified as to glare and in which proportionate weight has been given to the location of the source in the field of view, is included in the Illuminating Engineering Society's revised Code of Lighting. This Code was prepared by the Society to make available authoritative information for legislative bodies and others who are interested in regulations covering lighting and it also serves as a guide for factory owners and operators in improving the lighting conditions in their own plants. The Code is now an American Standard indorsed by the A. I. E. E. and many other national organizations. Tables III, IV, V and VI and the appended matter are reprinted from the Code.

TABLE III.

CLASSIFICATION OF LIGHT SOURCES FROM THE STANDPOINT OF GLARE

Grade I indicates sources of maximum softness.
Grade X indicates sources of maximum harshness.

Maximum Visible Brightness	Total Candle Power in Direction of Eye				
(Apparent candles per sq. in.)	Less than 20	20 to 50	50 to 150	150 to 500	500 to 2000
	Grade	Grade	Grade	Grade	Grade
Less than 2	I	I	II	II	III
2 to 5	II	II	III	IV	V
5 to 20	II	III	IV	VI	VII
20 to 100	IV	V	VI	VII	VIII
100 to 1000	V	VI	VII	VIII	IX
1000 and up	VI	VII	VIII	IX	X

In Table III, Light Sources are classified from the standpoint of glare, taking into account both the maximum visible brightness and the candle power in the direction of the eye. However, it is not con-

TABLE IV.

SPECIFIC CLASSIFICATION OF LIGHT SOURCES FROM THE STANDPOINT OF GLARE AS DERIVED FROM TABLE III

NATURAL LIGHT SOURCES

(As seen through windows or skylights)

	Grade
Sun	X
Very Bright Sky	V
Dull Sky	III
Sun Showing on Prism Glass	IX

OPEN GAS FLAMES	II

Incandescent Mantle Gas Lamps

	Mantles consuming 2-5 cu. ft. per hr.	Mantles consuming 5-8 cu. ft. per hr.	Large single mantle or cluster 8-12 cu. ft. per hr.	Large single mantle or cluster 12-20 cu. ft. per hr.	Cluster or high pressure lamp consuming above 20 cu. ft. per hr.
	Grade	Grade	Grade	Grade	Grade
Clear Glassware	V	VI	VII	VIII	IX
Frosted Globes	III	IV			
6-in. Opal Globe*	II				
8-in. Opal Globe*		III	IV-VI		
10-in. Opal Globe*	I	II	III-V	V-VII	VI-VIII
12-in. Opal Globe*					
Dome Reflector					
Mantle Visible	V	VI	VII	VIII	IX
Mantle not Visible	I	II	III	IV	IV
Bowl Reflector					
Mantle Visible	V	VI	VII	VIII	IX
Mantle not Visible	II	II	III	V	V
Totally Indirect*			I-II	II	III
Semi-Indirect Bowls*			II-III	II-IV	III-VI

*Where a range is given the best grade, that is the lowest, applies to globes that are evenly luminous, and the poorest to globes which have a decidedly bright spot in the center.

TABLE IV—*Continued*

ARC LAMPS

	Grade
Enclosed arcs, clear globes	IX
Flame arc, clear globes	X
Flame arc, opal globes	VII-VIII

MERCURY VAPOR TUBES	VI

CARBON AND METALLIZED FILAMENT INCANDESCENT LAMPS

8 c. p.	V
16 c. p.	V
32 c. p.	VI

Tungsten Filament Incandescent Lamps

Watts	10-25	40-60	75-100	150-200	300	500-1000
	Grade	Grade	Grade	Grade	Grade	Grade
Bare Lamps	VI	VII	VIII	IX	IX	X
Frosted Lamps or Frosted Globes	II	III	VI	VII	VIII	
8-in. Opal Globes*	I	I-II	II-IV	IV-VI		
12-in. Opal Globes*			II-III	II-V	IV-VI	VII-VIII
16-in. Opal Globes*				II-V	IV-VI	V-VII
Flat Reflectors—Filament Visible	VI	VII	VIII	IX	IX	X
Dome Reflectors—Steel or Dense Glass						
Filament visible from working position	VI	VII	VIII	IX	IX	X
Filament not visible from working position	I	I	III	III	IV	VI
Bowl Reflectors—Steel or Dense Glass						
Filament visible from working position	VI	VII	VIII	IX	IX	X
Filament not visible from working position	II	II	III	IV	VI	VII
Dome Reflectors—Bowl-Enameled Lamps			IV	V	VI	VI
Semi-Enclosing Units*			III-IV	IV-VI	IV-VII	VI-VIII
Totally Indirect Lighting*			I-II	I-II	II	III
Semi-Indirect Bowl*			I-III	II-III	II-IV	III-VI

*Where a range is given, the best grade, that is the lowest, applies to globes that are evenly luminous, and the poorest to globes which have a decidedly bright spot in the center.

venient in most cases to make the measurements necessary to determine which class a light source is in according to this table. Therefore another table has been shown in the Code, Table IV, in which specific light sources upon which the measurements have been made are listed with their grades.

Table V, Chart of the Field of View, classifies light sources according to their position in the field of view,

TABLE V.

CHART OF THE FIELD OF VIEW

Classification of Position of Light Source Which Takes into Account the Distance from the Eye and the Angle of the Line of Vision.

Height above Floor in Feet	Horizontal Distance of Light Source from Observer in Feet 1	2	3	4	6	8	10	12	16	20	25	30	35	40	50	60 & up
6.5 or less	A*	A*	A	A	A	A	A	A	A	A	A	A	B	B	B	B
6.5 - 7	G	E	D	C	C	B	B	B	B	B	B	B	B	B	B	C
7 - 8	G	G	F	E	D	D	C	C	C	C	C	C	C	C	C	C
8 - 9	G	G	G	F	F	E	D	D	C	C	C	C	C	C	C	D
9 - 10	G	G	G	G	F	F	E	E	E	D	D	D	D	D	D	D
10 - 11	G	G	G	G	G	F	F	F	E	E	D	D	D	D	D	D
11 - 12	G	G	G	G	G	F	F	F	F	F	E	E	D	D	D	D
12 - 13	G	G	G	G	G	G	F	F	F	F	E	E	E	E	E	E
13 - 14	G	G	G	G	G	G	G	G	F	F	F	F	E	E	E	E
14 - 15	G	G	G	G	G	G	G	G	G	F	F	F	F	E	E	E
15 - 16	G	G	G	G	G	G	G	G	G	F	F	F	F	E	E	E
16 - 17	G	G	G	G	G	G	G	G	G	G	F	F	F	F	E	E
17 - 18	G	G	G	G	G	G	G	G	G	G	G	G	F	F	F	F
18 - 19	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	F
19-20 and up	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

*Classifie as A unless light source is so nearly above the head of operator as to be quite outside of field of view in which case classify as E.

TABLE VI.

SHOWING LIMITING GRADES OF LIGHT SOURCES PERMISSIBLE FOR VARIOUS LOCATIONS

Classification of position	Space or work to be lighted. Roadways and yard thoroughfares	Storage spaces aisles, stairways, handling coarse material	Ordinary manufacturing operations†	Offices and drafting work and certain mfg. operations*
	Limiting Grade	Limiting Grade	Limiting Grade	Limiting Grade
A	VI	V	III	II
B	VII	VI	V	IV
C	VIII	VII	VI	V
D	IX	VIII	VII	VI
E	IX	IX	VIII	VII
F	X	X	IX	VIII
G	X	X	X	X

BACKGROUND

Where the background and the surroundings are very dark in tone, a light source of one grade softer than that specified in Table VI may be required. Where the background and surroundings are very light in tone one grade more harsh than that specified in the table may sometimes be permitted.

†For the present the limits set in this table cannot be rigidly applied to portable lamps used for temporary work such as setting up machines repairing automobiles, etc.

*Those operations in which workers are seated facing in one direction for long periods of time.

TABLE VI-A.
SHOWING GRADES OF LIGHT SOURCES WHICH ARE CONSIDERED GOOD PRACTICE FOR VARIOUS LOCATIONS

Classification of position	Space or work to be lighted			
	Roadways and yard thoroughfares	Storage spaces aisles, stairways, handling coarse material	Ordinary manufacturing operations	Offices and drafting work and certain mfg. operations
	Grade	Grade	Grade	Grade
A	IV	III	I	I
B	V	IV	III	II
C	VI	V	IV	III
D	VII	VI	V	IV
E	VIII	VII	VI	V
F	IX	IX	VIII	VI
G	X	X	IX	VIII

i. e., their horizontal distance from the observer, and their height above the floor. To be glaring, a light source must either be located in a position close to the eye or, if at a distance, it must lie within a small angle from the ordinary line of sight. Light sources in positions denoted by the first letters of the alphabet in Table V are close to the eye or close to the line of vision, and are most likely to be the cause of discomfort. Light sources in positions *E*, *F* and *G* are farther from the eye or without the direct line of vision and are less likely to cause glare.

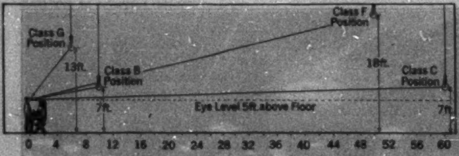

FIG. 6—TYPICAL POSITION GIVEN IN THE CHART OF THE FIELD OF VIEW, SEE TABLE V.

Table VI of the Code combines Tables IV and V and shows the limiting grades of light sources permissible for various types of work, when the light sources are located in the different positions in the field of view.

In addition Table VI-A which is not contained in the Code has been computed. This table shows the Grades which are recommended for various conditions. It should be used in preference to Table VI in planning new installations and in all other cases, except when the question is simply one of whether the lighting system is acceptable from the legal standpoint.

These tables may appear formidable, however, they are in reality very simple to use as may best be demonstrated by trying them out in one or two examples. For instance, consider the lighting in the machine shop of an industrial plant which is being inspected to find whether it comes within the requirements of the lighting code.

Because of the very low ceiling the lighting system which had been recommended by a competent engineer for this shop consisted of *R L M* dome reflectors with 150-watt bowl-enameled lamps mounted 8½ ft. above the floor and spaced 10 ft. apart. The owner of the plant, however, decided that he would save himself a little trouble by using clear lamps instead. Otherwise the lighting was installed as recommended. A number of machinists work in this room. Their work does not keep them in one position for a long period of time.

The inspector found that the most troublesome light source from the point of view of any one workman was the second[3] unit directly in front of his machine, at a horizontal distance of ten to twelve feet. Referring to Table V, the inspector found that for units located at a height of eight to nine feet and a horizontal distance of ten to twelve feet their position in the field of view is classified as *D*. By referring to Table IV, he also found that a dome reflector and 150-watt clear lamp the filament of which is visible, is classed in Grade IX, and again, that in Table VI under the column headed "Ordinary Manufacturing Operations" in the fourth line, opposite *D*, the harshest grade of light source which it is permissible to use is given as Grade VII. The lighting system in this plant, therefore, did not meet the Code requirements as far as provision against glare was concerned and the inspector's position was that the owner of the shop must change the lighting and he suggested that bowl-enameled lamps be installed as originally recommended. According to Table IV dome reflectors with 150-watt bowl-enameled lamps fall in Grade V which is well within the Code requirements and which, incidentally, is the grade of source which Table VI-A mentions as representing good practise for this class of service. It is of interest to note that one large manufacturing concern which recently rehabilitated its lighting found in the course of experiment that not only did the substitution of bowl-enameled lamps for clear lamps provide greatly increased comfort for the employees but it also resulted in a measurable increase in production in the departments where the change was made.

The following explanatory notes for the guidance of inspectors and industrial plant operators are taken verbatim from the I. E. S. Code.

"From Table IV the majority of bare incandescent lamps are seen to have a relatively poor rating; that is, most of them fall in Grades VII to IX, and it is evident from Table VI that Grades VII to IX are never to be permitted in work rooms in positions *A*, *B* or *C*. That is, the use of bare incandescent lamps is prohibited in working areas except when they are located at considerable heights above the floor or when they are so placed as to be out of the field of vision. At the present time it will be found necessary from a practicable standpoint to delay the strict enforcement of this provision in a very few instances, particularly in the case of extension cord lamps used in temporary work, such as in setting up machinery and in repairing automobiles, etc.

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[3] With a flat reflector the third or fourth unit ahead might have caused still greater discomfort on account of its closer proximity to the line of vision but with an R. L. M dome at a height of eight feet to nine feet the lamp filament in these more distant units is cut off from view by the skirt of the reflector.

"It will be noted from Table IV that the sources of natural light, side and ceiling windows, usually fall in Grade IV. This means (see Table VI) that no mandatory rules are established as to the use of shades, awnings, etc., except in those cases where the sky is visible through portions of the sash in position *A*, that is, less than 6.5 ft. above the floor, or where the sun itself comes within the range of vision.

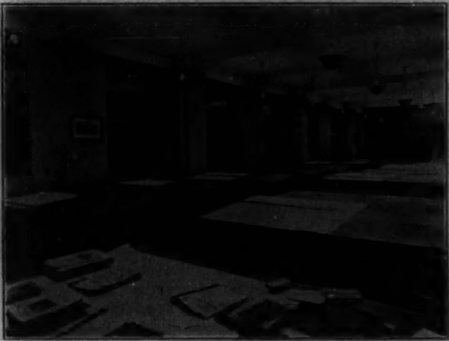

Fig. 7—An Ample Supply of Soft Well Diffused Light and Particularly Freedom from Shadows is Required for Drafting Rooms

"However, Grade II is the limiting value for light sources less than 6.5 ft. high, in offices, and other locations where the workers are seated facing in one direction for considerable periods of time. Hence, in these cases, to comply with the Table, the work must be so arranged that the employees are not required to face windows where the sky is visible through the lower sash; that is, less than 6.5 ft. above the floor.

Prism glass when so located as to catch the sun's rays ordinarily has a very much poorer rating than clear glass; hence, where it is used the installation of window shades or curtains should ordinarily be required.

"*Glare by Reflection.* Another way in which glare is produced is by the reflection of light from polished surfaces in the field of vision. The difficulty experienced in protecting the eyes from this kind of glare is sometimes very great. The brightness of the image on the working surface is, of course, proportional to the brightness of the light source above it, and hence one way in which to minimize this effect is to diffuse the downward light; that is, to use a bowl-frosted, or bowl-enameled lamp or an enclosing fixture, or to employ semi-indirect or totally indirect lighting fixtures. In some cases the light source can be so located that its reflection is directed away from, rather than towards, the eyes of the workers. The avoidance of highly polished surfaces in the line of vision is another good way to minimize reflected glare.

"There are some instances, on the other hand, where sharp shadows and specular reflection from the materials worked upon actually assist vision. For example in sewing on dark goods the thread is much more easily distinguished when illumination is secured from a concentrated light source, such as a brilliant lamp filament, which casts sharp shadows and gives rise to a distinct glint from each thread. However, in these cases the light source must be particularly well shielded from the eyes of the worker."

Lest in his efforts to minimize glare one should arrive at the conclusion that the best way of all to accomplish this purpose is to extinguish the lamp, the following quotations from the closing paragraphs of the Code are also included.

Advantages of Good Illumination

"While the advisability of good natural and artificial illumination is so evident that a list of its effects may seem commonplace, these effects are of such importance in their relation to factory management that they are worthy of careful attention. These effects of good illumination, both natural and artificial, and of bright and cheerful interior surroundings, include the following:

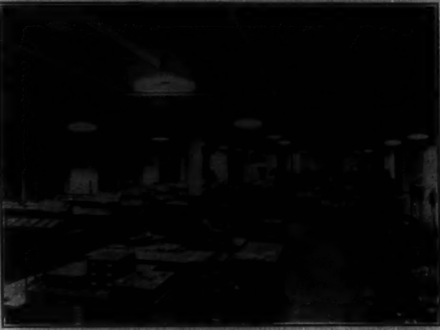

Fig. 8—Ample Illumination without Glare

"1. Reduction of accidents.
"2. Greater accuracy in workmanship, resulting in improved quality of goods.
"3. Increased production for the same labor cost.
"4. Less eye strain.
"5. Greater contentment of the workmen.
"6. More order and neatness in the plant.
"7. Supervision of the men made easier.

"While it is difficult to place a definite money value on the savings effected in increased production and improved quality, by good illumination, it by no means follows that such savings are insignificant or unsubstantial. The factory owner who ignores them neglects his own interests. Other items in the foregoing list, even more difficult to value definitely, are none the less real; taken together, they constitute a powerful argument in favor of the best available illumination."

Appendix

Let a_1, a_2 represent area of light source
b_1, b_2 represent brightness of background
c_1, c_2 represent candle power of source
d_1, d_2 represent distance from source to eye

I. Where the area of the source and its distance from the eye are held constant and the candle power of the source is varied then to maintain equality as to glare

$$\frac{b_2}{b_1} = \left(\frac{c_2}{c_1}\right)^{\frac{1}{\log 2}} = \left(\frac{c_2}{c_1}\right)^{3.3}$$

II. Where the brightness of the background and the distance from the eye to the source are held constant and the candlepower of the source is varied then

$$\frac{a_2}{a_1} = \left(\frac{c_2}{c_1}\right)^{\frac{1}{\log 2}} = \left(\frac{c_2}{c_1}\right)^{3.3}$$

III. Where the brightness of the source candle power per unit of area and the brightness of the background are held constant and the candle power of the source is varied then

$$\frac{d_2}{d_1} = \left(\frac{c_2}{c_1}\right)^{½} = \left(\frac{c_2}{c_1}\right)^{0.5}$$

IV. Where the candle power of the source and the brightness of the background are held constant, and the area of the source is varied then

$$\frac{d_2}{d_1} = \left(\frac{a_1}{a_2}\right)^{\frac{\log \sqrt{2}}{\log 5}} = \left(\frac{a_1}{a_2}\right)^{0.216}$$

V. Where the brightness of the background and the area of the source are held constant and the candlepower of the source is varied, then

$$\frac{d_2}{d_1} = \left(\frac{c_2}{c_1}\right)^{\frac{1}{2-2\log 2}} = \left(\frac{c_2}{c_1}\right)^{0.71}$$

Discussion

F. C. Caldwell: The lack of understanding on the part of the public of the whole problem of lighting was well brought out by Mr. Harrison's paper. One point needs a little more emphasis and that is the erroneous idea that glare is solely a function of brightness. Mr. Harrison has clearly demonstrated that the glare produced by excessive quantity of light is more serious than that produced by too great brightness. This is just one example of the general misapprehension of these simple laws on the part of even intelligent people.

H. Calvert: There is one statement, made in the first paragraph which may be correct, but does not appear to be so. I refer to the statement:—"they forget that the 200 candle power lamp of the present generates no more thermal units than did a single candle in the days of our forefathers." It would be interesting to know how this conclusion was reached.

G. H. Stickney: Glare in lighting represents an undesirable effect, which is readily recognized, but not so easily defined. In a general way there is more or less of an agreement as to what conditions of lighting constitute glare, but to express systematically, the relative importance of brilliancy, contrast, flux, position etc. as contributing causes, has so far baffled the illuminating engineer.

He recognizes that there are degrees of glare, that the glare encountered in one place is worse than that met in another. It, therefore, follows that there should be some way of measuring glare.

A glareometer which would give a reasonable measure, would be a great boon to the lighting art. It would not only facilitate research, but also would assist greatly in the specification of good lighting, the writing of codes, and the inspection of any individual lighting installation.

A number of engineers have given quite a bit of study to this problem, and have made brilliancy meters, contrast meters and pupil meters, but none of these, so far as known to the writer, has proved sufficiently comprehensive or practically applicable to various conditions. While it is still to be hoped that a suitable instrument will be forthcoming, the necessity of the art is such that, some other method, of at least classifying conditions in terms of the relative degree of glare, is required. This method, described by the author, seems to present the most practical scheme that has yet been suggested.

The scheme is really comparatively simple. From observation and experience, the various ordinary illuminants are graded from I to X with regard to their glare reducing powers. Then with a similar symbol, the permissible degree of various operations are tabulated, with reference to the position of the illuminant in relation to the eyes of the subject workman. This provides a means of deciding that a selected illuminant does not exceed the limits.

Of course, this is empirical and perhaps arbitrary, but at least it is fairly definite. It appears to be reasonable and in line with experience. In case later experience should show that certain changes in classification should be made, it would seem practicable to make such changes. But in the interest of practical utility, the author's classification should be adhered to for the present. Having been incorporated in the Illuminating Engineering Society's Industrial Lighting Code, now an American Engineering Standard, the glare classification seems to be ready for useful service.

On the other hand, it is to be hoped that research, which may lead to an absolute instrument or method, may be continued, neither interfering with the other until a real improvement is brought out.

Ward Harrison: Mr. Calvert asks about the relative amount of heat generated by a candle and an incandescent lamp of 200 times its intensity. The comparison is about as follows:

An ordinary paraffin candle 13/16 inches in diameter burns down at the rate of 1¼ in. or a little less than 0.025 pounds per hour. The generally accepted B. t. u. value for hydrocarbons such as paraffin is from 18,000 to 22,000 B. t. u. per pound; 20,000 × 0.025 equals 500 B. t. u., the approximate heat units liberated by a candle in one hour.

A 150-watt Mazda lamp generates 2100 lumens or approximately 200 horizontal candle power. The heat equivalent of one kw-hr. is 3410 B. t u., hence, the 150-watt lamp liberates 515 B. t. u. per hour or approximately the same amount as the candle. As a matter of fact, the ordinary paraffin candle gives about 10 per cent less light than the standard candle used in photometry, and furthermore, the art of candle making has improved considerably during the past 100 years.

Mr. Stickney emphasizes the desirability of a glareometer. Such an instrument is certainly much to be desired but it seems as if its mechanism must be possessed of an almost human brain in order to integrate brightness, flux, location in the field of view, etc. in the same way that we do.

Philadelphia-Pittsburgh Section of The New York-Chicago Cable

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Engineering and construction features involved in a complete telephone cable system over 300 miles in length and connecting Philadelphia and Pittsburgh, Pa. are described in the following paper. This cable is designed to operate as an extension of the Boston-Washington underground cable system with which it connects at Philadelphia. It is also designed for operation in connection with the Pittsburgh-Chicago cable now under construction, and other cable projects included in a comprehensive fundamental plan.

Beginning with the fundamental factor of public requirements for communication service between cities separated by various distances, there are next considered the methods available to provide this service. Small-gage, quadded, aerial cable, which was decided upon for use in this section after careful economic studies, is described in a general way and the important advantages of the application of loading and telephone repeaters are outlined. The use, in connection with this cable, of the recently developed metallic telegraph system for cables is referred to and some facts are given regarding power plants, test boards and buildings. A few of the many possible combinations of cable and equipment facilities into complete telephone circuits, which will furnish the service required as economically as now possible, are illustrated.

The necessity of complete coordination of the many factors involved in a project of this kind is emphasized.

INTRODUCTION

THE placing in service in the latter part of 1921 of the final section of a continuous telephone cable over 300 miles in length between Philadelphia and Pittsburgh marked a new point of achievement in the steady development and construction of facilities designed to render to the public the best possible long-distance telephone service. Furthermore, this cable forms an important part of a comprehensive plan of long-distance cable construction throughout that section of the United States lying in general east of the Mississippi River and north of the Ohio and Potomac Rivers.

In the discussion of a project of this kind which involves many new practises and the expenditure of several millions of dollars and which, with related work already completed, forms the groundwork for large expenditures in the future, it is usual to inquire first into the underlying reasons for carrying out the project and then into the methods adopted. In the following discussion an endeavor will therefore be made to furnish some information on these two items in their relation to the Philadelphia-Pittsburgh cable, although, as will be obvious, the many different points can be covered in only the most general way in the space available. However, before going ahead with the discussion, I would like to point out that this project is not unlike many others in that, as a whole and in the component parts, there have been required, first, the careful consideration and decisions of the executives, then the underlying work of many scientists, inventors and engineers, then the skilled work of the manufacturers and construction forces, and finally the maintenance and operation by trained people who are responsible for the

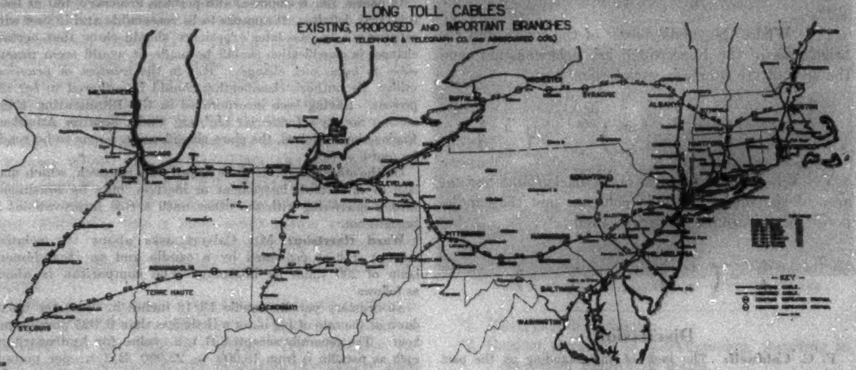

FIG. 1—ROUTES OF EXISTING AND PROPOSED LONG TELEPHONE CABLES

Presented at a meeting of the Philadelphia Section of the A. I. E. E., January 9, 1922, and at the Annual Convention of the A. I. E. E., Niagara Falls, Ont., June 26-30, 1922.

continuous service so vitally necessary to the industrial and social structure of the country. The point to be emphasized here is that the coordination of all of these factors and the close cooperation of all of the many hundreds of people concerned are the important things.

General Cable Plans and Routes

Fig. 1 is an outline map of a section of the United States and shows the routes of existing and proposed long telephone cables of the Bell system. It will be noted that the present and proposed routes follow in a general way the routes of trunk-line railroads. This general section contains more than 50 per cent of the entire population of the United States but less than 15 per cent of the area, and the industrial and telephone development is, of course, very great. Furthermore, the nearby surrounding states, supplying as they do large quantities of food products and raw materials, are commercially related to this section in a very peculiar way and this fact greatly influences the long-distance telephone development along the particular cable routes indicated. The routes through the State of Pennsylvania and the offices at Philadelphia and Pittsburgh, which are the terminals of the cable that is more particularly the subject of this discussion, occupy strategic positions in this system.

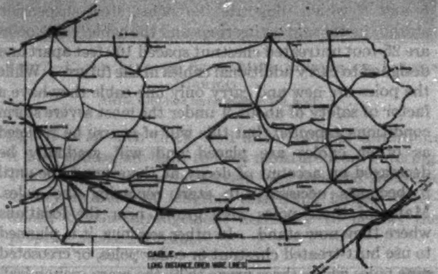

Fig. 2—Outline Map of Pennsylvania, Showing Aerial Line and Cable Routes

Circuits of the American Telephone and Telegraph Company and the Bell Telephone Company of Pennsylvania are carried over these routes and this cable was jointly planned and installed by these companies.

Fig. 2 is an outline map of the State of Pennsylvania and shows the situation in this section a little more in detail. On this map are shown some of the larger cities and routes of the longer and more important toll and long-distance telephone lines. As indicated, these lines are mainly of the familiar aerial wire type which has been generally used in the past for this purpose and which is today the most efficient and economical type of construction for many cases. In the general section between Philadelphia and Pittsburgh the requirements for circuits are very heavy and in addition, as is well-known, the topography of the country is such that the through routes which can economically be used for pole lines are limited. At present, these few routes are fully occupied by the pole lines of the various utilities and included in these lines are three fully loaded telephone trunk lines. Another item of importance in the consideration of aerial wire construction is the very severe damage frequently experienced in many sections of the country on heavy aerial wire lines from ice and wind storms. Even lines built with exceptional strength fail in these storms and the interruptions to service are serious matters to the users as well as to the telephone companies. The restoration costs under the conditions that naturally exist at such times are abnormally high.

Fig. 3—Damage to Section of New York-Boston Main Line Near Worcester, Mass.
Storm of November 28, 1921.

Fig. 4—Section of New York Boston Main Line Showing Wires Heavily Loaded With Ice
November 28, 1921.

Figs. 3 and 4 show the effects at one point of the ice and wind storm in New England on November 28, 1921, and are proof that this problem is real. This particular spot is near Worcester, Mass., and the line is a section of one of the principal aerial wire routes between New York and Boston. In this storm, many thousands of poles were broken and even where a few poles remained standing due to specially strong construction, the load of ice combined with the wind was too great for the wires to withstand. There is therefore a practical limit to the number of wires that can be safely and economically carried on a pole line.

FIG. 5—GENERAL VIEW OF POLE LINE CARRYING AERIAL CABLE

Where the practicable routes for pole lines are limited, where the existing pole lines are fully loaded, and where estimated future circuit requirements are of considerable magnitude, it is obvious that different methods of providing facilities, if available, must sooner or later be given serious consideration. The conditions between Philadelphia and Pittsburgh and in general along all of the cable routes shown on Fig. 1 are now, or are expected within a few years to be, such as to make the use of some type of construction other than aerial wire desirable for most of the circuits.

After careful studies of the circuit requirements for future periods and of the methods available for providing long-distance telephone facilities, which in general are aerial wire and cable, it has been decided that for relief in these sections the cable method will give the best and most economical results. Long underground cables, as is well-known, have been in operation for many years between Boston, New York, Philadelphia, Baltimore and Washington, Chicago and Milwaukee and in other sections. However, the type of cable and associated apparatus which is now being used in the development of the more comprehensive plan is quite different from that originally used between Boston and Washington and in the other sections, particularly in the use of copper conductors of a smaller gage combined with improved loading coils, the vacuum tube telephone repeater and other methods and apparatus which are the result of recent developments. Lead-covered aerial cable supported on wooden pole lines is to be used in general on all of the routes except in the two sections just mentioned and through cities or where special conditions exist for short distances. The possibility of now using conductors of No. 16 and No. 19 A. W. G. instead of conductors up to No. 10 A. W. G. as in the older cables, has contributed to make aerial construction rather than underground conduit the more economical in many sections, as one cable will provide for a much greater number of circuits and consequently fewer cables will be required.

LINE CONSTRUCTION

The general type of aerial construction which was used for over 250 miles of the total distance of 302 miles from Philadelphia to Pittsburgh may be seen from Figs. 5 and 6 which illustrate the poles, steel suspension strand, metal supporting rings and the cable. The poles are 25-foot untreated chestnut spaced 100 feet apart and designed to carry additional cables in the future. While the poles are new and carry only one cable they have a factor of safety of about 9 under the most severe storm conditions expected, but this will of course be reduced as other cables are placed and will gradually be decreased on account of decay at the ground line until it becomes necessary to start replacing the poles. Many of these poles were grown near the locations where they now stand. In other sections, it is planned to use butt-treated chestnut or cedar poles, or creosoted pine poles where these prove to be the more economical.

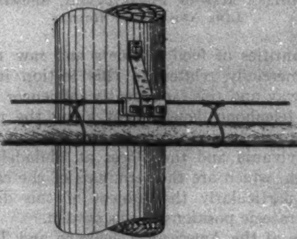

FIG. 6—METHOD OF SUPPORTING AERIAL CABLE AND MESSENGER

The galvanized steel suspension strand has a breaking strength of about 16,000 pounds and the actual tension under normal conditions is about 7000 pounds. In placing the strand, it is necessary to pull it to just the right tension in order that when the cable is hung it will have the proper sag. The correct tension is readily determined by what is known as the "oscillation" method. The metal rings are spaced 16 inches apart and the cable weighs about 7½ pounds per foot.

The size and make-up of the cable vary somewhat with the number of circuits of the various types that are to be provided in the different sections, but in general it is full size, that is, its over-all diameter is $2\frac{5}{8}$ in. which is about the maximum size of telephone cable. The sheath is of lead-antimony alloy, one-eighth of an inch thick, and under normal conditions it is, of course, air-tight to keep moisture from entering. The cable for the aerial section was received from the factory in 500-foot lengths, this being largely determined by the arrangement necessary to permit the proper installation tests.

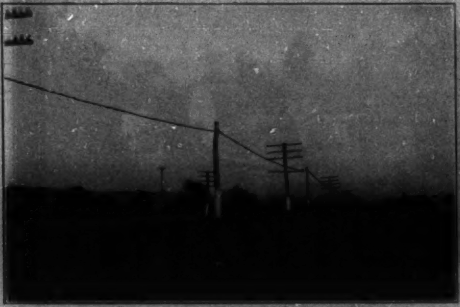

Fig. 7—Cable Line on Seven-Mile Stretch of Lincoln Highway

Aerial wire line to be dismantled later.

Fig. 8—Cable Line Across Valley at Grand View

ROUTE

We might next consider the route selected and for this purpose Fig. 2 will again be helpful. It will be noted that starting at Philadelphia, the cable is routed to Reading touching Pottstown, Phoenixville and other points. From Reading to Harrisburg the cable follows closely the William Penn Highway, although in sections it was necessary to obtain private right-of-way or to use longer routes removed from this highway on account of the lines of various kinds already in operation there. It is very desirable for economic reasons to keep the length of these cables as short as possible and in some cases this is absolutely necessary to obtain proper operating conditions. However, the most direct routes cannot always be used, for many obvious reasons, and this problem required careful consideration in all sections of the cable.

Fig. 9—Cable Crossing at Juniata River

Fig. 10—Cable Line on Steep Slopes

Between Harrisburg and Pittsburgh the Allegheny Mountains had to be crossed and for this crossing only two general routes were found practicable, the first following an existing pole line which is the New York—Chicago telephone line through Lewiston, Altoona, etc., and which we may call the northern route, and second a southern route through Shippensburg, Bedford and Ligonier for the most part along the Philadelphia-Chicago line and also the Lincoln Highway. A middle route which is now used for the Harrisburg-Pittsburgh line was not seriously considered as the country was too rough for economical construction and maintenance and no important advantages were to be obtained. After careful surveys and cost studies, taking into account all existing and anticipated conditions, such as circuit requirements and towns to be reached, length of practicable routes, maintenance conditions, freedom from probable physical and electrical interference, etc., it was decided to build on the southern route.

This route, while of nearly the same length as the northern one and offering some important advantages, was not free from difficulties as it crosses the Allegheny Mountains within a few miles of the highest point. Fig. 7 shows the cable line on what is known as the seven-mile stretch of the Lincoln Highway east of Ligonier, and here the going was fairly good. The Philadelphia-Chicago aerial wire line is also shown and two of the crossarms carrying 10 wires each are to be removed in the near future and the circuits operated in the cable. It is planned to remove the remaining two crossarms later on. Fig. 8 shows the cable across a valley and is taken from the point on the Lincoln Highway called Grand View. Fig. 9 shows the crossing of the Juniata River east of Bedford where special construction was used. Fig. 10 shows just one example of the conditions encountered in crossing the many mountains and a photograph does not do the scenery or the construction difficulties justice. On account of the steep slopes, clamps are used at many points to fasten the cable to the strand.

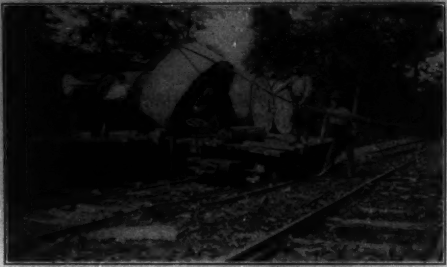

FIG. 11—NARROW-GAGE MOUNTAIN RAILROAD AND FLAT CAR

Narrow-gage timber railroads were used in the mountains where possible to get material to the job and Fig. 11 shows one of the regular flat cars adapted for our purpose. Fig. 12 shows two 5-ton tractors in action on top of one of the mountains. As many sections of the country are very rough and highways several miles distant it seemed that no other method of transporting the cable reels, which weigh nearly 5000 pounds, could possibly be used, and certainly no other means would have been as satisfactory. Even with these methods the cable reels could not always be delivered where desired and in some cases it was necessary to pull the sections of cable through the rings for a distance of nearly a mile to get them in place.

FIG. 12—TRACTORS PLACING CABLE REELS IN ROUGH COUNTRY

FIG. 13—PIECE OF CABLE WITH SHEATH PARTLY REMOVED

CABLE MAKE-UP

As stated before, the make-up of the cable varies somewhat with the circuit requirements in the different sections but the wires and arrangement in a typical section of cable are roughly illustrated in Fig. 13.

The cable is of quadded construction, that is, the wires are first wrapped with dry paper for insulation and twisted into pairs and then two pairs are twisted into what is called a quad. These quads are arranged in concentric layers as shown and great care and skill are required in the design and manufacture or there is certain to be serious cross-talk between the several hundred circuits when used for long-distance service. Even after the application of the best present manufacturing methods, tests are made on all circuits at three points in each loading section of 6000 feet while the cable is being spliced. These tests are made in order to determine the best possible arrangement of conductors for still further reducing cross-talk between circuits, and the splicing is done accordingly.

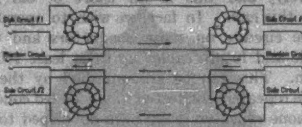

Fig. 14—General Phantom Circuit Arrangement
Four wires providing three circuits.

There are 19 quads of No. 16 A. W. G. and 120 quads of No. 19 A. W. G. pure copper conductors in one of the principal sections, and the arrangement of the four wires in each quad is such that two physical circuits and one phantom circuit are made available. The method of obtaining three telephone circuits from two pairs of wires is old and extensively used. It is illustrated in Fig. 14. The method results in a 50 per cent increase in the number of available circuits and its application to this project is therefore of very great economic importance. Now the total of 139 quads multiplied by 3 gives 417 circuits or as many as could be carried on about 14 heavily loaded pole lines if aerial wire were used, but as will be described later, we will have to use two of these circuits to make one telephone circuit in some cases where the distances are comparatively great, so it is expected that only about 300 telephone circuits will be obtained for regular service. This is as many as could be carried on 10 heavily loaded pole lines if aerial wire were used. It is now thought that in some sections this number of circuits will take care of future demands for about 10 years after allowing for the dismantling of some existing aerial wire.

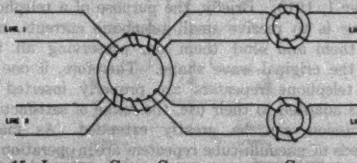

Fig. 15—Loading Coils Connected to a Group of Four Wires and Arranged for Phantom Operation

As these cables can be obtained in any size desired up to the maximum, the period for which they should be engineered can be determined from studies of circuit requirements and costs. These studies are of very great importance and the cost considerations include of course annual costs of the various plans over proper periods as well as first costs.

Loading

Loading coils are now connected to many of the circuits and all of the circuits in this cable are intended to be equipped with coils located at 6000-foot intervals. The theory and practise of loading are described in papers previously presented before the Institute[1] and for our purpose it will be sufficient to state that these loading coils very materially reduce the attenuation losses and improve the quality of transmission as compared to cable circuits not so equipped. The improvement in so far as the attenuation losses are concerned, varies with the type of circuit and loading coils, but with one of the No. 19 A. W. G. circuits in this cable loaded with coils having an inductance of 0.175 henry located at 6000-ft intervals, the losses are only about one-third as great as in a similar circuit without the coils. The connections and arrangements of the coils are shown in Fig. 15 and it will be noted that coils have been connected to both the physical and phantom circuits. The arrangement is such that there is no appreciable interference between circuits due to magnetic action in the iron cores of the different coils or to the necessarily close electrical relation in the windings.

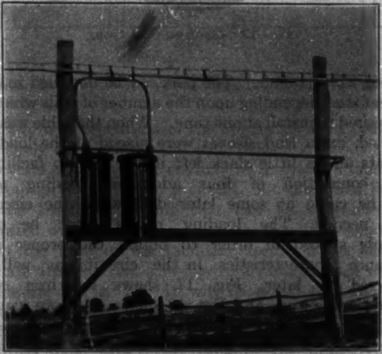

Fig. 16—Loading Fixture

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[1] Papers by M. I. Pupin, Transactions of A. I. E. E., XVII, May 1900 and XV, March 1899.

Paper by Bancroft Gherardi, Transactions of A. I. E. E., XXX, June 1911.

The loading coils are potted and sealed in iron pots, two of which are shown in Fig. 16, and in the country these are mounted on pole fixtures. Each pot contains 36 groups of 3 coils each. The pots are nearly 30 inches in diameter at the flange, 52 inches high and weigh about 2700 pounds. The pots can be obtained in different sizes depending upon the number of coils which it is desired to install at one time. When the cable was installed, extra lead sleeves were placed at the loading points and a little slack left in the wire to facilitate the connection of four additional loading pots to the cable at some later date when the circuits are needed. The loading points must be uniformly spaced in order to obtain the proper impedance characteristics in the circuits as will be referred to later. Fig. 17 shows the iron core of a loading coil, and Fig. 18 shows this core wound with insulated wire and then wrapped with cloth and the terminals brought out nearly ready for potting.

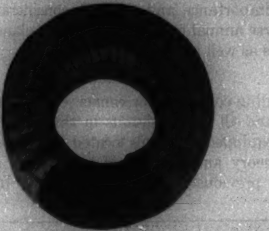

Fig. 17—Loading Coil Core

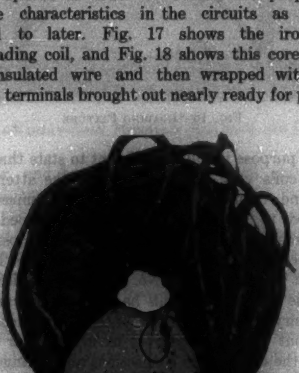

Fig. 18—Loading Coil with Winding Completed

Fig. 19 shows several coils arranged on one of the spindles which will be placed in the iron pot also shown. This particular pot will hold 7 spindles and when they are in place, the pot will be filled with compound and thoroughly sealed.

Telephone Repeaters

Even with the improvement in the quality of transmission and reduced attenuation losses effected by the use of loading coils, loaded cable circuits alone of No. 16 and No. 19 A. W. G. could be satisfactorily operated for distances less than 100 and 60 miles, respectively, and this is far short of our requirements in this case. In fact, we wish to operate some telephone circuits on these conductors and through this cable and future cables up to at least 1000 miles in length. This can be accomplished by the use of telephone repeaters connected to the loaded conductors.

Telephone repeaters have been developed to a high state of perfection and are completely described in a paper presented by Messrs. Bancroft Gherardi and Frank B. Jewett at a joint meeting of the A. I. E. E. and the Institute of Radio Engineers in New York, October 1, 1919. Briefly, the purpose of a telephone repeater is to receive small telephone currents, amplify them and send them on, preserving all the while the original wave shape. Therefore, if one or more telephone repeaters are properly inserted in circuits adapted to their use, the range of satisfactory transmission can be greatly extended. As many hundreds of vacuum-tube repeaters are in operation on the Philadelphia-Pittsburgh cable and connected cables, and as a great many more are planned for future installation, we will briefly consider the elementary features of some of the types of repeaters used.

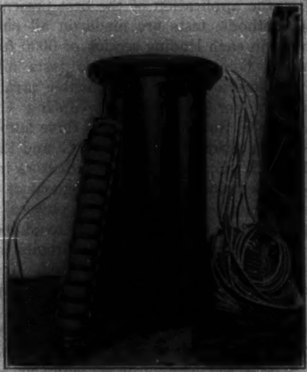

Fig. 19—Loading Coils on Spindle, Iron Loading Coil Case and Spindle Cables

Fig. 20 shows the structure of the vacuum tube which is an essential element of this type of repeater. It is a small glass bulb with a vacuum that is as good as is practicable to obtain. In the tube is a filament which is heated to incandescence during operation, and a grid and plate. The circuits directly associated with the tube are shown in more detail in Fig. 21, and this would constitute a device for amplifying currents from one direction. As is well understood, any change in the potential impressed on the grid causes a change in the current flowing in the plate-filament circuit. To obtain complete two-way repeater action two of these amplifier arrangements are combined with the circuits shown in Fig. 22.

FIG. 20—VACUUM TUBE

It will be noted that the line circuit from one direction, for instance, the one designated "line west," is connected through a three-winding transformer to a balancing network which is so made up as to balance the line as nearly as possible at telephone frequencies. This balance is essential to proper repeater operation. The circuit arrangement is such that part of the incoming energy is diverted to that part of the circuit containing the input coil directly associated with this three-winding transformer. By the action of the vacuum-tube arrangement amplified energy is transmitted to the line east. That part of the original incoming energy from the line west that goes through the balancing network or the output coil is not, of course, transmitted along into the line east. The operation in the case of currents incoming from the line east is similar and it will be noted that the complete repeater circuit is made up of two symmetrical parts. This circuit arrangement constitutes what is known as a two-wire repeater and the apparatus is, of course, all closely associated in the same office.

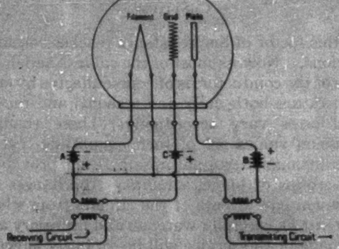

FIG. 21—VACUUM-TUBE REPEATER ELEMENT

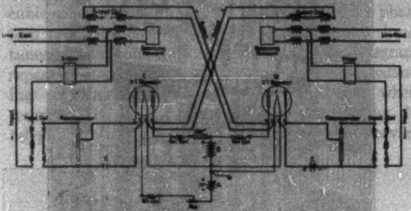

FIG. 22—TWO-WAY VACUUM-TUBE REPEATER CIRCUIT

Several of these repeaters may be inserted in tandem at appropriate points in a circuit, but there is a limit to the length of circuit that can be satisfactorily operated with this arrangement, this length depending upon the type of the facilities used. When longer circuits are required, a four-wire arrangement is used, as shown in Fig. 23. It will be noted that in this arrangement the three-winding transformers are not located in the same office but may be in offices several hundred miles apart. At each of the intermediate stations a vacuum-tube amplifier arranged for amplification in one direction only is connected to each of the two branches of the circuit. Two circuits are, of course, required between the terminals and these may be either physical or phantom circuits.

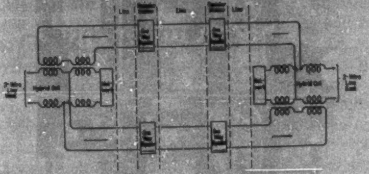

FIG. 23—FOUR-WIRE CIRCUIT

Equipped with telephone repeaters and arranged for connection to two-wire circuits at the terminals.

An advantage of this arrangement is that balancing networks are not required at each repeater station and the general matter of balance and consequently good repeater operation in the circuit as a whole is greatly simplified. This arrangement can, therefore, be satisfactorily used for long circuits where two-wire operation might be impracticable, and examples would be such circuits as New York-Pittsburgh or New York-Chicago.

Fig. 24—Group of Repeaters at Reading, Pa.

Both of these types of circuits may be operated on No. 19 A. W. G. four-wire facilities which may be either physical or phantom circuits.

Fig. 24 shows a group of repeaters installed in the office at Reading, Pa., and Fig. 25 shows one of the four-wire repeater units in somewhat greater detail.

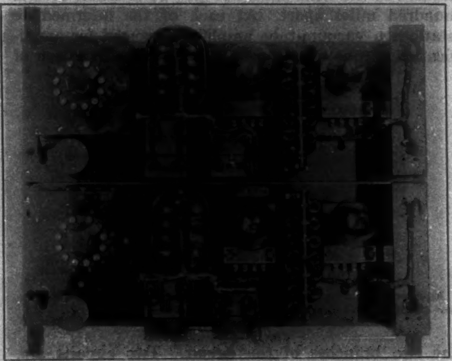

Fig. 25—Assembly of Four-Wire Repeater Apparatus

Line Impedance

In order that networks may be used to balance the lines for repeater operation, it is necessary as a practical proposition that the impedance characteristics of the lines be fairly uniform over the range of telephone frequencies. The solid line in Fig. 26 shows the resistance component of the impedance of a No. 19 loaded cable circuit with all loading coils in place. The solid line in Fig. 27 shows the resistance component found in impedance measurements on the same circuit with one coil omitted at the thirteenth loading point from the end at which the tests were made. It will be noted that in the latter case the characteristics of the circuits vary greatly with frequency. It would therefore be very difficult as a practical proposition to build up a network that would balance lines in this condition, and such variations in the electrical characteristics of a circuit impair the quality of telephone transmission, as the currents of different frequencies are differently affected. The necessity for careful maintenance work in promptly replacing loading coils which may become defective or preventing other irregularities from creeping into the plant will therefore be clear.

Transmission Regulation

The resistance of small-gage cable conductors is one of the important factors that determine the transmission losses of a circuit. The resistance of a No. 19 A. W. G. pair is about 88 ohms per mile so that in a long circuit this factor of line resistance reaches considerable proportions. Now as most of the cable is aerial, the resistance of the conductors is of course affected by changes in temperature both daily and seasonal and the transmission losses vary accordingly. These changes in transmission values are of such magnitude that automatic transmission regulators are being provided for certain groups of longer circuits. All changes in the transmission equivalents of the circuits from whatever causes must be carefully watched and necessary adjustments made or the service will be seriously affected.

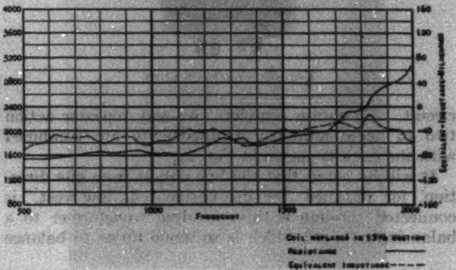

Fig. 26—Line Characteristics—A Cable Circuit in Normal Condition

Telegraph

In the section between Philadelphia and Pittsburgh practically all of the existing long aerial wire circuits are composited, that is, they are arranged for simultaneous telephone and telegraph operation. The telegraph circuits thus obtained are generally used in furnishing what is sometimes called "leased wire" service. The ground return system providing either full duplex or single-line operation is used and the line currents average about 75 milliamperes. This grounded telegraph system cannot be used where simultaneous telephone and telegraph service is desired on loaded cable circuits of the length involved in this cable, and as a part of the work of carrying out the comprehensive toll cable plans of the Bell system, a new telegraph system had to be developed. It was found preferable to use a metallic return circuit and to limit the line current to a value between 3 and 5 milliamperes in order to prevent serious interference to the telephone circuits due to the "flutter effect,"[2] Morse thump, and mutual interference between telegraph circuits. Morse thump results when the composite sets, that is, the apparatus used for separating the telephone and telegraph currents, do not completely prevent the latter from entering the telephone circuit, thus causing interference. The telegraph repeaters are located at about 100-mile intervals on the No. 19 circuits and at somewhat less frequent intervals on No. 16 circuits. The telegraph apparatus is of course located in the same buildings that are used to house the telephone repeaters, and on the Philadelphia-Pittsburgh cable telegraph repeaters will be located initially at Philadelphia, Harrisburg, Bedford and Pittsburgh.

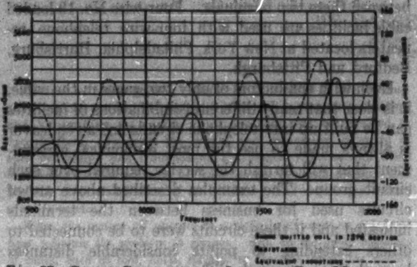

FIG. 27—CABLE CIRCUIT WITH LOADING COIL MISSING AT THIRTEENTH LOADING POINT FROM TERMINAL

FIG. 28—TEST BOARDS

TEST BOARDS

All of the conductors in the cables are carried into stations located at about 50-mile intervals and apparatus is provided in these stations for making regular tests to ascertain the condition of the cable and to locate trouble quickly. At these offices the different kinds of operating apparatus are also connected to the cable conductors; examples of this apparatus are phantom repeating coils, composite sets to permit simultaneous telephone and telegraph operation, telegraph repeaters, telephone repeaters and associated balancing equipment, signaling apparatus, and where required, the switchboards necessary for making the telephone connnections involved in furnishing service.

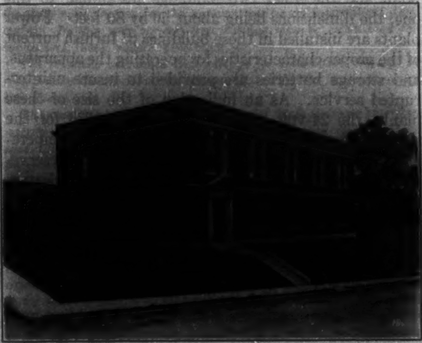

FIG. 29—TEST AND REPEATER STATION AT LIGONIER, PA.

It is necessary that this apparatus which is installed in large quantities be systematically arranged and facilities provided for making quick changes in the circuit arrangement. The circuits are wired through jacks installed in groups in test boards for this purpose and to facilitate testing. One of these boards is illustrated in Fig. 28. This particular board is located in one of the larger offices. The test boards in one of the repeater stations such as Bedford, would consist of a smaller number of positions. A position is three feet in length. In Fig. 28 each position bears a number.

STATIONS AND POWER PLANTS

Telephone repeaters of either the two-wire or four-wire type are connected to the circuits at approximate intervals of either 50 or 100 miles, depending upon the type of facilities which it is economical to use in the different circuits and the kind of service for which a given circuit is intended. As mentioned above, telegraph repeaters are installed at about 100-mile intervals. At some of these points existing offices are used while in a number of cases it was necessary to erect buildings for the sole purpose of housing the repeaters, testing apparatus and other equipment associated with the cable. For example, new buildings of fire-proof construction were erected at Shippensburg, Bedford and Ligonier. Fig. 29 is a view of the building at the latter point and the other two buildings are similar to this one, the dimensions being about 50 by 80 feet. Power plants are installed in these buildings to furnish current of the proper characteristics for operating the apparatus, and storage batteries are provided to insure uninterrupted service. As an indication of the size of these plants, the 24-volt storage batteries installed for the initial load at Bedford have a capacity of 2240 ampere-hours and this provides about one day's reserve. The capacity can, of course, be increased as repeaters are added from time to time when additional circuits are needed. Storage batteries of smaller sizes supplying current at potentials of 30, 120 and 130 volts are also provided.

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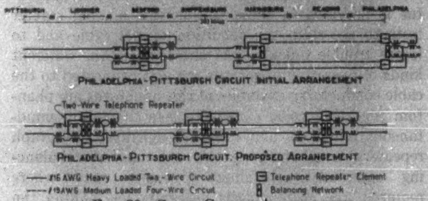
[2] Paper by Martin and Fondiller in JOURNAL of A. I. E. E., February, 1921.


PITTSBURGH
LIGONIER
BEDFORD
SHIPPENSBURG
HARRISBURG
READING
PHILADELPHIA
Two-Wire Telephone Repeater
#16 AWG Heavy Loaded Two-Wire Circuit
#19 AWG Medium Loaded Four-Wire Circuit
Telephone Repeater Element
Balancing Network

PHILADELPHIA-PITTSBURGH CIRCUIT INITIAL ARRANGEMENT

PHILADELPHIA-PITTSBURGH CIRCUIT. PROPOSED ARRANGEMENT

FIG. 30—CABLE CIRCUIT ARRANGMENTS

EXAMPLES OF CIRCUIT ARRANGEMENTS

Fig. 30 shows two possible methods of building up a Philadelphia-Pittsburgh terminal circuit and Fig. 31, a method of building up a New York-Pittsburgh terminal circuit. In all three cases these telephone circuits are intended to have a transmission equivalent of about 12 miles of standard cable. Some Philadelphia-Pittsburgh terminal circuits of the first type have been in everyday operation for several months, but it is not the most economical arrangement that it is possible to obtain for general use in providing this or similar service. It will be noted that No. 19 four-wire facilities are used between Philadelphia and Harrisburg and four-wire repeaters are located at these two points. At Harrisburg the four-wire circuit is connected to a No. 16 two-wire circuit with a two-wire repeater at Bedford. This arrangement was used in order to start service through the cable with the facilities available, but it is intended later on to use the arrangement shown in example No. 2.

In example No. 2, No. 16 heavily loaded conductors are used and two-wire repeaters are located at Reading, Shippensburg and Ligonier. The total transmission equivalent of this circuit without repeaters is about 50 miles of standard cable so that in order to obtain a net equivalent of 12 miles for the circuit each of the three repeaters must give a transmission gain of nearly 13 miles of standard cable. This circuit could not of course be used for telephone purposes without repeaters.

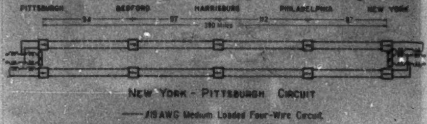
The third example shows how it is expected to operate New York-Pittsburgh circuits intended for business between these two terminals. Four-wire No. 19 loaded cable facilities are used with four-wire telephone repeaters located at New York, Philadelphia, Harrisburg, Bedford and Pittsburgh.

Even with conductors of only two gages in the cable, it is clear that many different combinations of facilities can be built up into telephone circuits and an endeavor is always made to use the most economical arrangement that will furnish the service required over each circuit group. The examples described above are of circuits used for business between the terminals indicated and if these circuits were to be connected to others extending to points considerable distances beyond these terminals different arrangements would be required. The cable conductors used in building up these telephone circuits can be composited and telegraph circuits are thus provided for simultaneous operation with the telephone circuits.

CONCLUSION

In the above discussion, an effort has been made to furnish some descriptive information regarding a complete cable system recently completed and now in successful operation between Philadelphia and Pittsburgh and designed for long-distance telephone and telegraph service. In one sense this discussion may be considered a report of the present status of the toll cable plant intended to connect Atlantic Seaboard cities with Chicago and other cities, and extensions are now under construction. However, most of the general methods which it is planned to use in these extensions are not expected to differ greatly from those described.

This cable system utilizes many new developments in the communication art and some of these, which have been briefly touched on here on account of their important application, have been described in more detail in previous papers. It is expected that more information regarding other specific developments which have contributed in an important way to the successful carrying out of this project or which may be utilized later on will be furnished in future papers.



NEW YORK - PITTSBURGH CIRCUIT

FIG. 31—CABLE CIRCUIT ARRANGMENTS

An important feature of this cable project is the fact that while many new developments and practises are utilized, the design of the system as a whole is such as to fit in economically with existing wire and cable systems and proposed extensions.

A Method of Determining Resultant Input from Individual Duty Cycles and of Determining Temperature Rating

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Consulting Engineer, New York

Review of the Subject.—*Before it is possible to put a group of motors into service, it is necessary to provide means for generating and transmitting the energy which probably will be required to operate them. To select the proper and economical capacity of such generating and transmitting equipment, requires that some reasonably correct estimate be made of the probable amount and probable time distribution of the combined load due to the motors when in service.*

When the motors all operate in a definite sequence on a definite time schedule the problem is simple. But, in the great majority of cases, such as tool, hoist, elevator or traction drive, the motors comprising the group do not in general operate in any such connected sequence. They operate more or less at random.

It is usual to estimate the probable load under such conditions of random, or approximately random, operation by guess work controlled only by experience and by comparison with load records obtained from similar installations already in operation. In general this method of estimating from records is not satisfactory.

In the first place such records, if sufficient for the purpose, are expensive to obtain and are not always available. In the second place, they are generally records of effects and not of causes. Whereas, as is shown in the paper, if the causes are known, the effects can be foretold with surprising accuracy. If certain average duty cycle characteristics of the motor application are known, as they must be known to make an intelligent selection of the motors for the required duty, then, by a simple application of the formulas of probabilities, it is possible to determine the characteristics of the energy input to any group of such motors.

No very great refinement in determining the average duty cycle for the individual motors in the group is required, for, if the number of motors or the number of observations of actual duty cycles be reasonably large, the average deviation from the mean will be small.

It is found that the method proposed gives calculated results that check quite closely with measured results. Not only can the average input, and from this the probable power consumption in kilowatt-hours be determined, but also the r. m. s. or heat generating value of the load as well as the probable amount and frequency of the peaks. Furthermore, data may be obtained for plotting in advance the most probable time distribution of load similar to a graphic instrument record.

The whole method is based on a determination of the average value of the **operating factor** *for the group of motors under consideration. The operating factor is the ratio of the average time any motor is running to the average duty cycle period. The operating factor may be averaged over any group of motors or, its average value may be determined from a graphic instrument record, such as obtained from a graphic wattmeter or ammeter. The value of the average operating factor is a better measure of the variations of load or input to a group of motors than either demand factor or diversity factor. In fact, it is shown that the value of the demand factor is generally meaningless and misleading.*

The value of the operating factor seems to lie within fairly narrow limits over numerous cases of the same kind of motor application. The demand factor does not possess this character.

Having thus established a method of rating the current-carrying and protective devices handling the input to a group of motors, it is necessary to establish a method of similarly rating conductors and protective devices handling the input to individual motors in the group. In other words, it is necessary to determine the heating value of any given intermittent duty cycle in terms of a continuous duty having equal heating value. The ratio between these two duties is found as a ratio of duty cycle factors expressed in terms of the operating factor for the individual duty cycle. In the continuous duty the operating factor is unity, and the duty cycle factor is also unity.

Since current-carrying devices are generally temperature rated in terms of continuous duty, it becomes possible to re-rate all such devices for other than continuous duty by operations performed on the duty cycle factors for the non-continuous or intermittent duty cycles. In this way various time ratings may be established for conductors, fuses, motors, generators, etc.

The resulting calculated time ratings for conductors prove to be very nearly the same as ratings established for the same times by actual tests.

The resulting calculated time ratings for fuses indicate how very narrow is the possible field for fuses as protective devices where continuous heavy overloads are not to be passed without rupture. In general it is impossible to use one set of fuses to protect a motor against more than 25 per cent continuous overload unless the starting peak is almost negligible. The result is quite in accord with general observation and test. It is shown that the underwriter's method of selecting fuses generally introduces a hazard rather than a safeguard.

NEW TERMS. Two new terms have been introduced, the **operating factor** *and the* **duty cycle factor.** *The operating factor not only determines the ratio of average load to total wired load, but also determines the ratio of r. m. s. load to the average load, as well as the amount, duration and frequency of peaks. In a sense, it is also a measure of operating efficiency.*

The duty cycle factor is merely a means of approximating the r. m. s. value of the duty cycle without resorting to the planimeter or to tedious graphical methods.

TABULATED DATA. Tables of values of the various factors entering into the probability formulas used are presented in an appendix, as well as tables for the computation of duty cycle factors.

NEW MATTER. It is believed that this paper presents for the first time an application of the theory of probabilities to the starting and stopping of motors. The theory of probabilities, or of statistics, has many possible applications in engineering which, of necessity, deals largely with statistical averages. The use of the theory in engineering has been strangely neglected.

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Preliminary Note

Assuming a group of motors whose individual duty cycles are known, operating at random or nearly so, it is necessary to determine the resultant combined duty cycle in order to select the most suitable capacity of the conductors feeding the group, as well as the rating and type of the generating apparatus supplying the required energy, and of the protective apparatus. The average value and r. m. s. value of the resultant duty cycle are required, as well as the maximum peaks, their duration and probable frequency of occurrence, together with some knowledge of the probable time distribution of the input. With such information available, even if it be only reasonably approximate, some intelligent selection of generating, distributing and protective equipment is possible. If the heat absorption and heat radiation constants of the current-carrying parts of the equipment are known, then the desirable rating of such parts on a basis of temperature rise may also be determined. Without such information the selection of equipment is largely a matter of guess work, more or less intelligent, depending upon experience and available records.

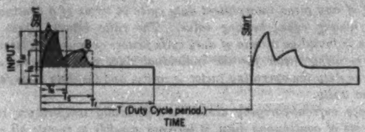

Fig. 1—Individual Duty Cycle
First Approximation.

While the method proposed is worked out in detail for the case of a group of similar motors, all operating at random on the same duty cycle, it is obvious that, with suitable and not very serious complications, it can be applied to groups of dissimilar motors operating at random on different duty cycles, such as motors driving diversified machine tools. The method, as given, applies without change to traction systems.

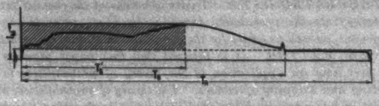

Fig. 2—Oscillogram
Direct-drive, 1 to 1 roping, traction-type elevator.

The Individual Duty Cycle

The curve in Fig. 1 represents the average time distribution of the input to all of the individual motors in the group. The average time per cycle or between starts is T. The average time during the cycle when the motor is running is T_r. The average starting period is T_s. The average running input during the time T, omitting the starting peak, is i. The average input during the starting time is I_s. The average starting peak input above i is $I = I_s - i$.

If, in the resultant duty cycle of the group, the maximum value reached by the resultant peaks is of more importance than their duration, the value of I_s is to be changed to I_M, the maximum peak input; in which case $I_P = I_M - i$. As a first approximation, the duration of I_M is then taken at T_s^1 so that the area A between I_M and i is equal to the area B enclosed by the actual curve of peak input and i. Then in both cases, the product of input and time is the same. But, if the actual maximum input is of short duration, the resultant maximum peaks for the group found in this way will be too steep and of too long a duration.

For many cases, such as that shown in Fig. 2, this first approximation will be sufficient. This is an oscillograph of input to a direct-drive, 1 to 1 roping, traction-type elevator hoisting engine on resistance speed control. The error here introduced by considering the starting input to be constant and equal to the maximum input over a reduced starting period is negligible. But in cases like that shown in Fig. 3, a second approximation may be required. In this case the starting peak below I is averaged as I_s over the time T_s and the starting peak I_M above I is drawn of such duration, T_s^1, that the area A enclosed is equal to the area B of the actual peak above I. The total area is then the same as the actual peak area above i.

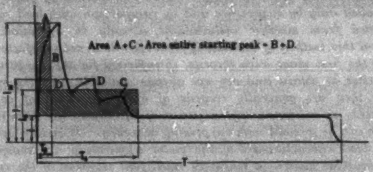

Fig. 3—Individual Duty Cycle
Second Approximation.

Obviously some judgment will be required in determining the approximation to be used. But without some such approximation the calculation of the resultant duty cycle becomes too cumbersome for practical use.

Another approximation has been introduced in considering the duty cycle used to be the average duty cycle for the group. If the group is divided into subgroups in each of which the motors are operating on very different average duty cycles, the calculations must be carried out for each sub-group separately and then combined. This difference may be in the time-distribution of the input during the duty cycle, in the duration of the duty cycle, or in both.

If the motors vary widely in capacity then a second sub-division into groups of motors of approximately the same capacity must be introduced and a separate calculation made for each such sub-group.

When the motors in the group number 20 or more in general no such sub-divisions of average duty cycles or capacities are necessary, unless a few relatively large motors may introduce a periodic large increase in the resultant input. In such special cases the particular motors must be treated as a sub-group.

In special cases it may be advisable to introduce approximations other than those above indicated. Again, if the starting peaks are not material or are relatively short, and particularly where, in such cases, the number of motors is large, it may be sufficient to average the entire input during the duty cycle, including the peak, and to omit from consideration the peaks above this average. If the peaks are of moment then at least two calculations are necessary, one for the average running input, i, and, depending on the order of approximation introduced, one or more for the peaks. The resultant duty cycles, one obtained by each such calculation, are then to be combined to obtain the over-all duty cycle. But in each case the method of calculation is the same, and, as will be seen from the case worked out below, is quite simple.

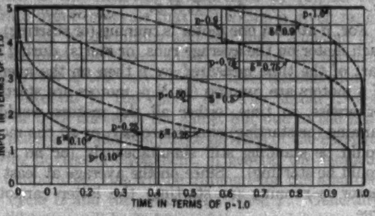

FIG. 3A—GROUP DUTY CYCLES
For $N = 5$, $i = 1.0$

METHOD OF CALCULATION

The method proposed is precisely the same as that used in determining the probable frequency of occurrence of any number of points in any number of throws of a given number of dice. As is well-known, this method very closely approximates to actual experience when the number of throws or trials is sufficiently large.

Let there be N motors in the group (or sub-group), the average duty cycle for which (Fig. 1) has the approximate values T, T_r, i, I_M, and let the duration of I_M be T_s^1. Then, on the average, each motor is running a fraction of the time given as a decimal by

$$T_r/T = p \tag{1}$$

This is also the average decimal of the total period considered, P, say 15 minutes or one hour as the case may be, during which any one motor in the group is running. If T and P be given in seconds, then P/T is the average number of duty cycles performed by each motor in the group in the time P. Since there are N motors in the group the total number of starts or runs made is

$$P/T \times N = R \tag{2}$$

The number R corresponds to the number of trials or throws of the dice in the analogous dice problem.

Since, on the average, each motor is running a part of the time P denoted by p, the probability that any one particular motor is running at any particular time is p. But there are N motors in the group. So the relative frequency in the total number of trials or observations, R, that any one motor is running is $N\,p \times R$.

Since, on the average, each motor is running a part of the time P denoted by p, the probability that any motor is running at any particular time is p. The probability that it is standing still at any particular time is $(1 - p)$.

The probability that any particular two motors are running simultaneously at any particular time is p^2. Similarly the probability that any particular set of r motors are running simultaneously at any particular time is p^r. Since there are N motors in the group, the probability that they are all running simultaneously at any particular time is p^N.

The probability that any particular set of r motors are standing still simultaneously is $(1 - p)^r$. The probability that all of the N motors are standing still simultaneously is $(1 - p)^N$.

The probability that any particular set of r motors are running simultaneously, while the remaining $(N-r)$ motors are standing still simultaneously is $p^r . (1 - p)^{N-r}$ But there are ${}^NC_r$ combinations of motors in the group taken either r or $(N - r)$ at a time, so the relative frequency with which the input due to r motors running simultaneously will occur, is

$$P_r = {}^NC_r \,.\, p^r \,.\, (1 - p)^{N-r}\,* \tag{3}$$

It is not difficult to compute and tabulate, or chart, values of (3) over a useful range of N, r and p.

In general if $\{(1 - p) + p\}^N$ be expanded as a binominal thus: $\{(1 - p) + p\}^N = (1 - p)^N + N\,p\,(1 - p)^{N-1} + {}^NC_2\,p^2\,(1 - p)^{N-2} + \ldots + {}^NC_r\,p^r\,(1 - p)^{N-r} + \ldots + p^N$, (4)
the first term is the probability that all the N motors are standing still; the second term is the probability that one motor is running and $(N - 1)$ motors are standing still simultaneously; the third term is the probability that two motors are running simultaneously and $(N - 2)$ motors are standing still simultaneously; . . . . ; the last term is the probability that all the N motors are running simultaneously. The sum of the terms in (4) is 1.0.

All of this is quite obvious, of course, to those who are familiar with the elements of the Theory of Probabilities.

Having determined the values of the terms in (4) as

$$*\left({}^NC_r = \frac{N\,(N-1)\,(N-2)\,.\;.\;.\;.\;(N-r+1)}{r\,(r-1)\,(r-2)\,.\;.\;.\;.\;1}.\right)$$

$P_0, P_1, P_2, \ldots, P_r, \ldots P_N$, they may be taken respectively as the probability that the input to the group at any time may be that due to no motors running or zero input, that due to one motor running, that due to two motors running simultaneously, ..., that due to r motors running simultaneously, ..., that due to all the N motors running simultaneously.

To determine the probable time distribution of the resultant input proceed as follows:

There are R chances in the period P that the input will change (see (2) above). Of these chances the input will be probably that due to no motors running (zero load), $P_0 \times R$ times; the input will be probably that due to one motor running $P_1 \times R$ times; the input will be probably that due to two motors running simultaneously $P_2 \times R$ times; . . . . . ; and the input will be probably that due to all the N motors running simultaneously $P_N \times R$ times.

Then, if $P = 1.0$ hour, chances are that $P_0 \times R = F_0$ times per hour the input will reach zero; the chances are that $P_1 \times R = F_1$ times per hour the input will be that due to one motor running; the chances are that $P_2 \times R = F_2$ times per hour the input will be that due to two motors running simultaneously; . . . . . ; and the chances are that $P_N \times R = F_N$ times per hour the input will be that due to all the N motors running simultaneously. These results may be changed into time distribution by considering that n times per hour equals every $3600/n$ seconds.

Such calculations having been carried out for the running current, similar calculations are to be made for the starting peaks, repeated twice if two approximations have been introduced as explained above (see Individual Duty Cycle).

In the case of the starting peaks

$$T_s/T = p_s, \text{ and } T_s^1/T = p_s^1 \qquad (5)$$

giving the values of p for the two approximations both of which are different from the value of p found for the running current. The corresponding values of ${}^N C_r \, p_s^r \, (1 - p_s)^{N-r}$, and ${}^N C_r \, p_s^{1r} \, (1 - p_s^1)^{N-r}$ will be different from each other and different from the values of ${}^N C_r \, p^r \, (1 - p)^{N-r}$ found for the running input. In this case, the input per motor is $I_M - i = I_p$ if only one approximation is used (see Fig. 1). If two approximations are necessary the two values are $I_s - i$ for the first approximation, and $I_M - I_s$ for the second (see Fig. 3).

AVERAGE INPUT

The average input over the time P is found as follows; two calculations are necessary, one for the running input and one for the starting input.

First as to the running input:

Of the total time P, zero input exists for the time $P_0 \times P$; the input due to one motor running exists for the time $P_1 \times P$; the input due to two motors running simultaneously exists for the time $P_2 \times P$; . . . . . ; and the input due to all N motors running simultaneously exists for the time $P_N \times P$.* Each of these results is to be multiplied by their respective values of input o, i, $2\,i$, ... , $N\,i$, and the sum of the products taken. This sum, divided by P, is the average input. It is

$$\frac{(P_0 \times P \times 0) + (P_1 \times P \times i) + (P_2 \times P \times 2\,i) + \ldots + (P_N \times P \times N\,i)}{P}$$

$$= i(P_1 + 2\,P_2 + \ldots + N\,P_N) \qquad (6)$$

Similar calculations, using I_p instead of i in (6), must be carried out for the average starting input which is to be added to the average running input to get the total average input.

SIMPLIFIED METHOD OF DETERMINING THE AVERAGE INPUT

If $p\,T \times R$ or $T_r \times R$ is greater than P, so that on the average at least one motor is always running, the average running input A_r may be determined by

$$A_r = i\,N\,p \qquad (6a)$$

If $p_s\,T \times R$ or $T_s \times R$ is greater than P so that on the average at least one motor is always starting, the average starting input, A_s, may be determined by

$$A_s = I_p\,N\,p_s \qquad (6b)$$

For, if at least one motor is running (or starting) and each motor on the average runs (or starts) during that part of the time measured by p then on the average, $N\,p$ motors are running (or $N\,p_s$ motors are starting). Otherwise, in time, either all the motors would be running (or starting) simultaneously, or all the motors would be standing still simultaneously (or no motor would be starting). Since on the average at least one motor is running (or starting) the latter cannot be true.

When the motors all perform one average duty cycle, the determination of A_r or A_s by (6a) and (6b) respectively is simple. But when the duty cycles vary widely so that the ratings of the motors vary widely, these formulas, like (6), must be applied separately to each group of motors for which an average duty cycle may be taken. (See Average Duty Cycle above).

From the average input thus determined, the approximate power consumption in kilowatt-hours during the period P may be found; determinations of this kind have proved to be within 10 per cent of the actual yearly power consumption of groups of motors in service.

ROOT-MEAN-SQUARE-INPUT

As in finding the average input, separate calculations for the r. m. s. running input, and for the r. m. s. starting input are necessary.

The values of $P_0 \times P$, $P_1 \times P$, ... , and $P_N \times P$ are determined as above. Then each value is multiplied by the *square* of its respective input. The sum of these products divided by P is the mean-square input, and the square root of this is the root-mean-square input. It is

$$\left\{\frac{(P_0 \times P \times 0) + (P_1 \times P \times i^2) + (P_2 \times P \times 4 i^2) + \ldots + (P_N \times P \times N^2 i^2)}{P}\right\}^{1/2}$$

$$= i\,(P_1 + 4\,P_2 + 9\,P_3 + \ldots + N^2 P_N)^{1/2} \qquad (7)$$

Similar calculations using I_p instead of i in (7), must be carried out for the r. m. s. value of the starting input, and added to the r. m. s. running input to get the total r. m. s. input.

Of course an error is introduced by treating a distributed series of equal load values as if the heating due to the distributed series were the same as a continuous load of the same amount, but lasting a single interval equal to the sum of the separate intervals. This error is not material for values of R equal to or greater than 1000. If R is much less than 1000 then it may be advisable to plot the actual load curve and determine temperature rise from the actual resultant duty cycle thus obtained.

The method assumes that the heating value of the distributed load as shown by curve T in Fig. 5, is the same as the heating value of the curve H shown in this same figure. Curve H is obtained by assembling together in one interval, as expressed by (6), all the separate input intervals that fall within a given range of input for both running and starting. Thus all the separate intervals during which the input lies between 200 and 300 in the curve T have been assembled as a single interval in the curve H. The actual r. m. s. value of both curves is the same, but due to the heat absorption and radiation characteristics of the current-carrying devices or equipment, in general the momentary temperature rise will be different for the assumed duty cycle H and the actual duty cycle T. Generally this difference will be in favor of the actual duty cycle. For instance, a fuse that would blow if subjected to the duty cycle H, would not blow if subjected to the duty cycle T. A fuse subjected successfully to a current of 600 amperes for a second or two at comparatively long intervals would blow if subjected to this same current for 7.2 seconds continuously.

The curve H may be considered as the characteristic frequency curve of input distribution in the particular case for which it has been determined. If curve-drawing instrument charts, giving time distribution of input to any group of motors, is available, the H curve may be determined graphically from the observed input distribution, exactly as it is determined above from the calculated input distribution.

For various values of N and p taking i as 1.0, characteristic H curves may be computed and graphed for comparison with H curves determined by observation. A selection of the appropriate standard H curve for any observed value of N determines the approximate over-all value of p for the group of motors under observation.

Such standard group duty cycles for $N = 5$ and various values of p are shown in Fig. 3A. These curves assume $p_s = 0$, or that the starting peaks are of no material moment. These curves are determined for $P = 1.0$ and $i = 1$.

Method of Plotting Time Distribution of Input

The various possible probable values of input as calculated above, namely, that due to one motor running, that due to two motors running simultaneously, ... , and that due to N motors running simultaneously, may then be spotted on a cross-section sheet taking one border as time and the other as input. These points establish the probable beginning of each change in input. The input remains constant till the next change occurs.

This square topped input curve may then be converted into a curve more resembling an actual curve-drawing instrument record by plotting the resultant input values at equal time intervals, say every two seconds, or five seconds, and by drawing straight lines between these points. If there are two groups or more for which the same calculations have been made, then the resultant input curves should be drawn on the same sheet for each group and their separate values at equal time intervals added to obtain points on the total curve.

A similar, and separate curve is then to be plotted for the peak input, and added to the running curve.

Such curves, plotted from computed probable values of input, may be compared properly with actual curve-drawing instrument records of input only with the understanding in mind that the computed value of the input at any time during the resultant cycle is the most probable value at that time. It should be compared only with the average of the values of the actual input at the same or corresponding intervals. In other words, the form of the computed curve of time distribution of input is the most probable form of the actual record curve.

Frequency of Combined Running and Starting Inputs

Having determined, as explained above, the probable frequencies P_0, P_1, P_2, ... etc. for both running and starting inputs, the frequency with which any combination of running and starting inputs will probably occur can be determined by multiplying together their separate frequencies. Thus, to determine the probable frequency with which the input due to r motors running simultaneously, and the input due to q motors starting simultaneously will occur at the same time, the value of P_r for the running input, and the value of $P\,q$ for the starting input are to be multiplied to get $P_{q,r}$. This may then be converted into terms of "times per hour."

Applications

The method outlined has been applied to actual installations of motors where the calculated results could be checked by comparison with records from curve-drawing and integrating instruments. The computed values always compare very favorably with the actual operating averages. In this, there is nothing strange, for the method of probabilities always leads to results that closely correspond to experience, and experience consists of just such statistical averages.

Example. Consider the case for which $N = 6$, $T = 20$ sec., $T_r = 10$ sec., $P = 3600$ sec., $i = 100$, and, to the first approximation, let $I_M = 200$, for $T_s{}^1 = 5$ sec. Then $p = 10/20 = 0.5$; $p_s = 5/20 = 0.25$; $R = 3600/20 \times 6 = 1080$.

The first step in the calculation is to determine values of ${}^NC_r\, p^r\, (1-p)^{N-r} = P_r$ for $p = 0.5$. They are

1. $P_0 = (1-p)^N = 0.5^6 = 0.015625 = 0.0156$ nearly
$P_1 = {}^6C_1 \times 0.5 \times 0.5^5 = 0.093750 = 0.0938$ “
$P_2 = {}^6C_2 \times 0.5^2 \times 0.5^4 = 0.234375 = 0.2344$ “
$P_3 = {}^6C_3 \times 0.5^3 \times 0.5^3 = 0.312500 = 0.3125$ “
$P_4 = {}^6C_4 \times 0.5^4 \times 0.5^2 = 0.234375 = 0.2344$ “
$P_5 = {}^6C_5 \times 0.5^5 \times 0.5 = 0.093750 = 0.0938$ “
$P_6 = {}^6C_6 \times 0.5^6 = 0.015625 = 0.0156$ “

1.000000

These values of P_0, P_1, P_2, etc. have been plotted in Fig. 4. It will be seen that because $p = 0.5 = (1-p)$ the resulting curve is symmetrical with respect to the maximum value of P_3. The most probable running input is that due to three motors running simultaneously. In this case it is also the average input.

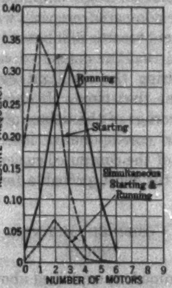

Fig. 4—Frequency Curves for Six Motors

$p = 0.5$, $p_s = 0.25$

The next step is to determine values of $P_r \times R = F_r$. They are

2. $F_0 = 0.0156 \times 1080 = 16.85$ times
$F_1 = 0.0938 \times 1080 = 101.30$ “
$F_2 = 0.2344 \times 1080 = 253.05$ “
$F_3 = 0.3125 \times 1080 = 337.50$ “
$F_4 = 0.2344 \times 1080 = 253.05$ “
$F_5 = 0.0938 \times 1080 = 101.30$ “
$F_6 = 0.0156 \times 1080 = 16.85$ “

Now the trials, $R = 1080$ occur in 3600 seconds or 1 hour, so from (2);

3. 16.85 times per hour is equivalent to every 213.6 sec.
101.30 “ “ “ “ “ “ “ 35.5 “
253.05 “ “ “ “ “ “ “ 14.2 “
337.50 “ “ “ “ “ “ “ 10.7 “
253.05 “ “ “ “ “ “ “ 14.2 “
101.30 “ “ “ “ “ “ “ 35.5 “
16.85 “ “ “ “ “ “ “ 213.6 “

Therefore the running input will probably reach that due to no motors running or zero input, every 213.6 sec.; it will probably reach that due to one motor running, or 100 amperes every 35.5 sec.; it will probably reach that due to two motors running simultaneously, or 200 amperes every 14.2 sec.; . . . . . . ; it will probably reach that due to all six motors running simultaneously, or 600 amperes every 213.6 sec.

It is to be noted that zero input and that due to all the six motors running simultaneously occur with the same frequency. This is also true of the input due to two motors running simultaneously, and the input due to four motors running simultaneously. In such cases either one or the other input is equally likely to occur.

The average running input by (6) is

$$100\,(0.0938 + 2 \times 0.2344 + 3 \times 0.3125 + \ldots + 6 \times 0.0156) = 300 \text{ amperes.}$$

Note that by (6a), $A_s = 100 \times 3 = 300$.

The root-mean-square running input, by (7), is

$$100\,(0.0938 + 4 \times 0.2344 + 9 \times 0.3125 + \ldots + 36 \times 0.0156)^{1/2} = 324 \text{ amperes.}$$

Similar calculations must now be made for the starting peak input. Here $p_s = 0.25$, so the values of ${}^NC_r\, p_s{}^r\, (1-p_s)^{N-r}$ are

4. $P_0 = (1-p_s)^6 = 0.75^6 = 0.1780$
$P_1 = {}^6C_1 \times 0.25 \times 0.75^5 = 0.3564$
$P_2 = {}^6C_2 \times 0.25^2 \times 0.75^4 = 0.2966$
$P_3 = {}^6C_3 \times 0.25^3 \times 0.75^3 = 0.1234$
$P_4 = {}^6C_4 \times 0.25^4 \times 0.75^2 = 0.0308$
$P_5 = {}^6C_5 \times 0.25^5 \times 0.75 = 0.00411$
$P_6 = {}^6C_6 \times 0.25^6 = 0.002285$

These results have also been plotted in Fig. 4. The resulting curve is unsymmetrical (skew) with respect to the most probable value, P_1. The most probable starting input is that due to one motor starting.

The next step is, as before for the running inputs,

2. $F_0 = 0.1780 \times 1080 = 192.24$ times
$F_1 = 0.3564 \times 1080 = 384.91$ “
$F_2 = 0.2966 \times 1080 = 320.33$ “
$F_3 = 0.1234 \times 1080 = 133.27$ “
$F_4 = 0.0308 \times 1080 = 33.26$ “
$F_5 = 0.00411 \times 1080 = 4.44$ “
$F_6 = 0.00229 \times 1080 = 1.57$ “

Then,

3. 192.24 times per hour is equivalent to every 18.7 sec.
384.91 “ “ “ “ “ “ “ 9.4 “
320.33 “ “ “ “ “ “ “ 11.2 “
133.27 “ “ “ “ “ “ “ 28.1 “
33.26 “ “ “ “ “ “ “ 108.2 “
4.44 “ “ “ “ “ “ “ 812.0 “
1.57 “ “ “ “ “ “ “ 2300.0 “

Therefore the starting input will probably reach zero every 18.7 sec.; it will probably reach that due to one motor starting every 9.4 sec.; it will probably reach that due to two motors starting simultaneously every 11.2 sec.; . . . . ; it will probably reach that due to all six motors starting simultaneously every 2300 seconds.

The average starting input, by (6) is

$$100\ (0.356 + 2 \times 0.297 + 3 \times 0.123 + \ldots + 6 \times 0.0023) = 148 \text{ amperes}$$

Note that by (**6b**), $A_s = 100 \times 1.5 = 150$.

This is to be added to the average running input of 300 amperes to get the total average. It is 448 amperes.

The root-mean-square starting input, by (7), is

$$100\ (0.356 + 4 \times 0.297 + 9 \times 0.123 + \ldots + 36 \times 0.0023)^{1/2} = 183 \text{ amperes.}$$

which is to be added to the r. m. s. running input of 324 amperes to get the total r. m. s. It is 507 amperes.

The kilowatt-hours consumed by the motors in any period during which these conditions hold can be determined from the total average input. It will be found to check very closely with the power consumption of the actual motors in actual service as measured by a watt-hour meter. The conductors feeding the group should be selected on the basis of the total r. m. s. input. The average drop in these conductors will be a function of the total average input.

The periodicity of peaks for this case may be worked out as follows:

The heaviest possible running input of 600 amperes due to six motors running simultaneously occurs every 213.6 seconds, the corresponding value of P_6 is 0.0156. Starting peaks may be added to this. Four motors start simultaneously every 108.2 sec. The corresponding value of P_4 is 0.0308. The probability that both will occur together is the product $0.0156 \times 0.0308 = 0.0048$. This has a probable frequency of $0.0048 \times 1080 = 5.18$ times per hour, or every 695 seconds; which is equivalent to once every 11.6 minutes. Its duration will be less than $T_s{}^1 = 5$ sec.

For six motors running and five motors starting simultaneously, the probable frequency is $0.0156 \times 0.0041 = 0.000064$. This is equivalent to 0.069 times per hour, or once every 52174 sec.; which is equivalent to once every 14 hours and 30 minutes. The corresponding input is 1100 amperes. It is probable that for most purposes this peak can be neglected.

The time distribution of input for this case is shown in Fig. 5. The curve *R* is the running input. The curve *S* is the starting input. The curve *T* is the total input. Greater peaks will appear if the curve is extended, due to the combination of running and starting peaks.

The method of plotting may be illustrated by the curve *R*. Referring to column *3* in the calculations for running input, it is found that zero input occurs every 213.6 sec. and that the input due to one motor running or 100 amperes occurs every 35.5 sec. The corresponding points *b*, *b*, *b*, ... are plotted. Then the load of 200 amperes due to two motors running simultaneously is plotted every 14.2 sec. . . . Since the input every 35.5 sec. is equally likely to be either 100 or 300 amperes, the two values have been plotted alternately. The same is true of the input every 14.2 sec. which is equally likely to be either 200 amperes or 400 amperes.

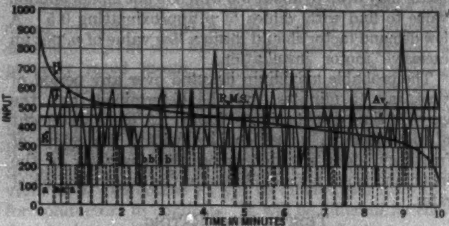

FIG. 5—TIME DISTRIBUTION OF INPUT
$N = 6$. $T = 20$ sec., $T_r = 10$ sec., $T_s = 5$ sec.
$p = 0.5$, $p_s = 0.25$, $i = 100$. $I_p = 100$.
Curve *T* plotted in 6-sec. intervals.

As explained above (Method of Plotting Time Distribution of Load), the square topped curve *R* is drawn through these points.

The starting input curve *S* is plotted and drawn in a similar manner.

Then, at every 6.0-sec. interval ordinates have been drawn and the sum of the input values given by the intercepts of these ordinates with the *R* and *S* curves, laid off as the corresponding ordinates of the curve *T*.

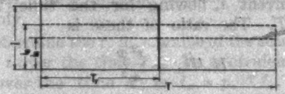

FIG. 6—CONSTANT-CURRENT DUTY CYCLE

DEMAND FACTOR

From the above discussion it will be seen that unless a statement of so called "demand factor" is coupled with a statement of frequency and duration, it means nothing and is more likely to be misleading than helpful.

In the above case, if the motors are rated for temperature rise, as they should be, by the r. m. s. input per motor, their rated input will be 84.5. If they are rated by the average input per motor their rated input will be 74.6, nearly 10 less, and equivalent to a continuous overload of over 13 per cent, involving an increase in temperature of about 23 per cent.

Commonly they will be rated by guess work and will be about twice too big for their work, involving increased annual charges and reduced efficiency.

If the motors are rated at 84.5, their united input is 507. A demand equal to 507 will probably occur at least every 15 minutes, for which the demand factor is 1.0. But the duration of this demand will be only a few seconds at most.

If the motors are rated by guess work this demand factor may drop to about 0.5 which is not an uncommon value to find with values of p approximating 0.5. A low demand factor should mean a low value of p, not an excessive motor installation.

The probable maximum demand over any period of time, say 15 minutes, may be determined from the curve of time distribution of input. A mere statement of such demand, unless coupled with a statement of frequency, does not determine the character of the input, and is not a logical basis for the determination of rates.

TEMPERATURE RATING

Consider the individual duty cycle shown in Fig. 6. The input i is constant for the time $T_r = p\,T$. The equivalent average input for the time T is i_a. The heat liberated by the current i for the time $p\,T$ is $H_i = C\,W\,i^2\,p\,T$, where C is a constant and W the resistance of the circuit. Similarly, the heat liberated by the current i_a flowing for the time T is $H_a = C\,W\,i_a^2\,T$. The ratio of these is

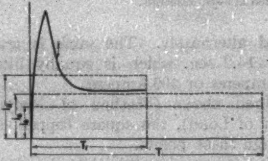

FIG. 7—VARIABLE-CURRENT DUTY CYCLE

$$H_i/H_a = \frac{i^2\,p}{i_a^2}\,.$$

But $i_a = p\,i$. Therefore $H_i/H_a = 1/p$.

Obviously more heat is liberated by the current i flowing for the time $p\,T$ than is liberated by the equivalent average current i_a flowing for the longer time T. The smaller is p the greater is this difference.

Assume that it is desired to determine the value of the current flowing for the time T that will liberate the same amount of heat as the current i flowing for the time $p\,T$. Let this desired current be i_e. Then $i^2\,p\,T = i_e^2\,T$, or $i^2/i_e^2 = i/p$. Therefore $i/i_e = (1/p)^{1/2}$

If, as in Fig. 7, the current i is not reasonably constant during the time $p\,T$, find its r. m. s. value i_R. Then $i_R/i_e = (1/p)^{1/2}$.

This is the basis on which conductor temperature rating may be established.

If the current i_e flows in indefinitely, the conductor will reach maximum temperature t_e in the time P_t depending on its radiation constant, etc. If in any case, conductors or fuses, the value of T should be greater than P_t, while $p\,T$ is less than P_t, then a new value of p must be found. It is $p_t = p\,T/P_t$. Then, for equal heat generation, the basis for rating is $i_r/i_{et} = (1/p_t)^{1/2}$, where i_{et} is the equivalent constant current for the time P_t. If $p\,T$ is longer than P_t then i_r is the same as the equivalent constant current. This would be the case for the distribution curve T in Fig. 5. Here the duty cycle period is taken at 15 min. But the input does not reach zero, so the r. m. s. value of input is the required equivalent constant-current rating. Otherwise than as pointed out above, the value of T does not enter into the formulas. It does not matter whether $p\,T$ be 5 seconds, 10 minutes or longer, provided T does not exceed P_t.

When, as in nearly all actual duty cycles, the starting peak is too pronounced to permit figuring it in as a slight increase in i during the time $p\,T$, the heat liberated by the peak must be computed separately. If the r. m. s. of the peak, in addition to the average running current i_a, is I_{pr} for the time $p_s\,T$, where, as above, $p_s = T_s/T$, then the equivalent constant current for the time T is $I_s = p_s^{1/2}\,I_{pr}$. The total equivalent constant current is then $I_{et} = i_e + I_s = i\,p^{1/2} + p_s^{1/2}\,I_{pr}$ (or if necessary, i_R may be used instead of i). The value of I_{pr} may be given in terms of i (or i_R) as $I_{pr} = c\,i$. Then $I_{et} = i\,(p^{1/2} + c\,p_s^{1/2})$. It is proposed to call the term $(p^{1/2} + c\,p_s^{1/2})$ the "duty cycle factor," and write it d. That is $I_{et} = i\,d$, or $i = I_{et}/d$. By taking I_{et} to be the rated constant current given in the N. E. C. Table I in Rule 18-b, then, by giving various values to d the appropriate rating of all such conductors can be determined for the corresponding duty cycles for which the actual running current is i, and the duty cycle factor is d.

It is assumed that in no case does T exceed P_t, or the time required to bring any conductor to its maximum allowable temperature with rated constant current flowing. If T is longer than P_t, new values of p and p_s must be found. If T_r is longer than P_t, then i or i_r is the equivalent running current, but a new value p_{st} must be found for p_s. The duty cycle factor then becomes $d = (1 - c\,p_{st}^{1/2})$.

We may then write down such conductor ratings, giving quite arbitrary values to d. The following table gives the corresponding ratings for a few rubber-covered conductors in conduit.

TABLE I

Size	N. E. C. Rating $d = 1.0$	Ratings for value of d			
		$d = 0.866$	$d = 0.706$	$d = 0.50$	$d = 0.25$
No. 14	15	17	20	30	60
No. 12	20	23	26	40	80
No. 10	25	29	33	50	100
No. 8	35	40	46	70	140
No. 6	50	57	66	100	200
No. 4	70	80	92	140	280
No. 2	90	100	110	180	360
2/0	150	172	197	300	600
4/0	225	258	300	450	900
0.3/0*	275	316	362	550	1100
0.6/0*	450	518	592	900	1800

It is of interest to check these results with time ratings arrived at by test. Assume that $P_t = 30$ minutes. This is a safe assumption particularly for the larger sizes. Assume a duty cycle such as shown in Fig. 6 and let T be equal to P_t. For this duty cycle I_{pr} and p_s vanish, and $d = p^{1/2}$. The time ratings will be given by $i_{et} = i/p^{1/2}$ where i is the N. E. C. rating. The value of p is given by T_r/P_t.

The calculated results marked "Cal." are given below for various values of T_r, together with test results marked "Rep." taken from the Report of the Committee on Demand Factor Western Association of Electrical Inspectors, dated Aug. 20, 1920.

TABLE II

Size	N. E. C. Rating $d = 1.0$	Ratings for values of T_r in minutes							
		Cal. 22.5 min.	Rep. 30.10 min.	Cal. 15 min.	Rep. 15 min.	Cal. 10 min.	Rep. 10 min.	Cal. 5 min.	Rep. 5 min.
14	15	17	19	20	22	26	24	36	30
12	20	23	24	25	26	33	29	49	35
10	25	29	30	33	35	43	40	61	45
8	35	40	43	46	50	61	60	85	65
6	50	57	66	66	73	85	80	121	105
4	70	80	77	92	97	120	110	170	140
2	90	100	106	110	130	156	155	210	195
2/0	150	172	179	197	220	264	260	365	340
4/0	225	258	256	300	325	389	395	550	515
0.3/0″	275	316	345	362	435	475	536	670	690
0.6/0″	450	518	610	592	750	780	915	1100	1225

The average deviation of the calculated results from the test results in the columns for 15 min., 10 min. and 5 min. respectively are − 29 amperes, + 9 amperes and + 2 amperes. The over-all agreement is remarkably close. Lack of knowledge of the method and refinement of the test referred to in the report mentioned, makes it impossible to compare individual results.

It is evident that the assumption $P_t = 30$ min. is somewhat low and probably too general. If P_t is increased the calculated results for the same values of T_r will be reduced.

It will be seen that if the rated continuous current and the value of P_t for any current-carrying device is given, the proper rating of the device for any other duty cycle for which d is known may be easily determined.

The duty cycle factor may be applied to a motor, thus: If the motor be name-plate rated at A amperes for M minutes, then M is the value of P_t for the motor. Let T, T_r, T_s, i_r and I_{pr} be determined for the duty cycle on which the motor is to operate. Then if T is no longer than P_t, the values of p and p_s may be taken from the duty cycle, and the duty cycle factor d determined. Then if A is no less than i_r/d, the given motor will carry the imposed duty for the time P_t without exceeding its rated temperature. If the duty cycle only is given then $A = i_r/d$ is the required rating for the time P_t of the proper motor for this duty. In general P_t will be taken as the time during which the duty will be imposed and may include a number of successive duty cycles.

If the value of P_t for a given type of motor is determined, the motor will carry the imposed duty cycle for a time P longer than P_t if $A = i_r/d \times P_t/P$ is the motor rating for the time P_t.

THE R. M. S. RATING OF FUSES

All that has been said above is equally true of the rating of fuses. Thus a fuse rated at 100 amperes constant current will also properly serve to protect a properly rated motor, for which $d = 0.25$ and $I_{et} = 200$ amperes. A larger fuse than this will not properly protect the motor against overheating. Therefore in selecting the proper fuse protection of a motor it is necessary to know not only its rating, but also its probable duty cycle of input and the corresponding value of d. Of course P_t will be different for fuses and for conductors in conduit. It will be different for conductors in conduit and for exposed conductors.

In cases where T is relatively long, it will be found that usually the starting peak has little effect in determining the value of I_{et} and can be neglected. If therefore, the rating of fuses, as now required by the Underwriters' rules, is based rather on the average value of starting peak than upon the value of I_{et} or total equivalent constant current, a fuse will be selected that will not protect the motor against undue temperature rise due to prolonged overloads. Numerous cases of such failure of fuse protection have been noted.

Consider the case in which $p = T_r/T = 0.64$ and $p_s = T_s/T = 0.16$. Determine the average running current i during the time T_r. Assume it to be nearly constant during the time $T_r - T_s$ so its r. m. s. value i_r may be taken equal to i. The equivalent constant current value for the time T is $i_e = p^{1/2} i = 0.8\, i$, on which basis a fuse may be selected for the running current only.

Now determine the r. m. s. value of the starting input I_{pr} above i over the time T_s. Its equivalent constant current over the time T is $I_s = p_s^{1/2} I_{pr} = 0.4\, I_{pr}$. Assume that $I_{pr} = 2.0\, i$ (or $I_{pr} = 2.0\, i_n$ if the running input during the time $T_r - T_s$ had been irregular enough to require that i_n be used instead of i). Then $I_s = 0.8\, i$ and the total equivalent constant current I_{et} is $1.6\, i$. Obviously the fuse to be selected would have little if any value during the running period as a protection to the motor against overloads up to 160 per cent of load.

Yet, if a smaller fuse be selected it will not carry the motor over its duty cycle. There are three possible solutions of this difficulty. 1. Let the motor start one set of fuses and run on another set of different rating. Quite generally the proper capacity of the running fuses will be larger than the proper capacity of the starting fuses. 2. Instead of the fuses, use a circuit breaker set to come out only if an excessive overload lasts for a period sufficiently long to overheat the motor. This may be accomplished by the use of time limit relays. The third, and usual, solution is to use an oversized or underrated motor, capable of standing overloads for sufficient time to bring to rupturing temperature the fuse of the capacity required to carry over the total duty cycle.

The following table gives the equivalent constant current rating of fuses in terms of the average (or r. m. s.) running input i, for various values of the root-mean-square of the starting peak I_{pr} expressed in terms of i as overload, and for various values of P_{st}. It is assumed that T, or the running time of the motor, exceeds P_t, or the time it takes the fuse, rated at i amperes, to reach maximum rated temperature. In other words, so far as the fuse is concerned, after start the motor runs continuously. The rating formula then becomes $I_{st} = i + p_{st}^{1/2} I_{pr}$ or $I_{st} = i + p_{st}^{1/2} c\,i$ where $c\,i = I_{pr}$. Then $I_{st} = i\,(1 + c\,p_{st}^{1/2})$.

TABLE III

p_{st}	Values of $I_{pr} = c\,i$ (overload during start) $0.25\,i$	$0.50\,i$	$0.75\,i$	$1.00\,i$	$1.25\,i$	$1.50\,i$
0.10	$1.08\,i$	$1.16\,i$	$1.24\,i$	$1.32\,i$	$1.39\,i$	$1.48\,i$
0.20	$1.11\,i$	$1.22\,i$	$1.34\,i$	$1.45\,i$	$1.56\,i$	$1.67\,i$
0.30	$1.14\,i$	$1.27\,i$	$1.41\,i$	$1.58\,i$	$1.69\,i$	$1.82\,i$
0.40	$1.16\,i$	$1.32\,i$	$1.47\,i$	$1.63\,i$	$1.79\,i$	$1.95\,i$
0.50	$1.18\,i$	$1.35\,i$	$1.53\,i$	$1.71\,i$	$1.89\,i$	$2.06\,i$
0.60	$1.19\,i$	$1.39\,i$	$1.58\,i$	$1.77\,i$		
0.70	$1.21\,i$	$1.42\,i$	$1.63\,i$			
0.80	$1.22\,i$	$1.45\,i$				
0.90	$1.23\,i$	$1.47\,i$				
1.00	$1.250\,i$	$1.50\,i$				

Thus, if the r. m. s. starting peak of any motor is 25 per cent overload (in terms of the actual constant running current i) that is, if $I_{pr} = c\,i = 0.25\,i$, and if the duration of this peak, T_s, is $p_{st} = 0.70$ of P_t, then a fuse must be used whose equivalent constant-current rating is $1.21\,i$. That is to say the motor may run continuously at 21 per cent overload (in terms of i) without exceeding the required fuse rating.

The Underwriters' rules permit the marked rating of a fuse to be 80 per cent of its equivalent constant-current rating. In other words the fuse will carry 25 per cent over its marked rating indefinitely. Such equivalent ratings are included above the upper dotted line in the table. A fuse whose marked rating is i will serve in all such cases. It is also understood that approved fuses shall blow instantly at 50 per cent overload. Equivalent ratings less than this are included above the lower dotted line. Thus, for $I_{pr} = 0.75i$ (75 per cent motor overload during start) and $p_{st} = 0.40$ or $T_s = 0.4\,P_t$, a fuse rating must be used that will permit a continuous running overload of 47 per cent. A fuse rated at less than this will not permit the motor to start and run for the time P_t. If, on the other hand, the motor can operate successfully at a continuous reasonable overload, a larger fuse must be selected provided it is concluded that the motor may start and carry this overload for any material part of the time P_t.

Assume this overload is $0.10\,i$, then the formula becomes $I_{st} = 1.1\,i + p_{st}^{1/2} I_{pr}$. For $p_{st} = 0.70$, and $I_{pr} = 0.55\,i$, the value of I_{st} is found to be $1.56\,i$. In other words, the fuse will permit the motor to run at 56 per cent overload. In general the r. m. s. value of the starting peak will also increase under such conditions, requiring a fuse still larger than this.

It is probable that for all conditions contained between the broken lines in the table double fuse arrangements should be used; either this or circuit breakers with time limit relays, the latter being always used for cases below the second dotted line.

As an example, consider an induction motor driving a pump. Assume that the running input after the water is in motion at normal velocity is 100 amperes per phase at 80 per cent power factor, therefore, the heating value of the input must be based on $i = 125$ amperes per phase. Let the motor be started by a compensator, or step reactance, so that the r. m. s. starting input will be 250 amperes at an average power factor of 60 per cent. The heating value of this input must be based on 425 amperes. Then, $I_{pr} = 425 - 125 = 300$ amperes. Therefore $I_{pr} = 300/125 = 2.4\,i$, (a value not given in the table). Assume that the duration of the starting period T_s, is 5 seconds. Assume $P_t = 15$ sec. Then $p_{st} = T_s/P_t = 0.33$, and $p_{st}^{1/2} = 0.57$.

The resulting value of $I_{st} = i + p_{st}^{1/2} I_{pr}$, is $125 + 0.57 \times 2.4 \times 125 = 296$ amperes. Therefore a fuse whose actual rating at $P_t = 15$ sec. is 300 amperes, will serve to start the motor and run it, but will also permit 300 amperes, or more than double full-load running input, to flow continuously. If a fused marked at 300 amperes for the same value of P_t were used it would pass 375 amperes continuously. A fuse marked 250 amperes will pass 300 amperes continuously and is probably the best rating to use, if a single set of fuses is required. As a matter of protecting the motor against prolonged over loads, one set of starting fuses rated at $0.57 \times 2.4 \times 125 = 171$ amperes may be used. Actually a fuse marked 150 amperes would serve. For the running side, a fuse marked 125 amperes would be the nearest safe size. Of course, if the name-plate continuous duty rating of the motor exceeds 100 amperes at 80 per cent power factor, larger fuses can be used with safety on both starting and running sides, remembering that since the motor will be operating at fractional load, the power factor during both start and run, under the actual duty conditions, will be lower than those given. If P_t is greater or less than the assumed value of 15 seconds, the value of I_{st} will be altered correspondingly.

TABLE IV—1.
Values of p^r and $(1-p)^{N-r}$

r or (N − r)	p	(1 − p)	p	(1 − p)	p	(1 − p)	p	(1 − p)	p	(1 − p)
	(1 − p)	p	(1 − p)	p	(1 − p)	p	(1 − p)	p	(1 − p)	p
1	0.05	0.95	0.10	0.90	0.15	0.85	0.20	0.80	0.25	0.75
2	0.25×10^{-2}	0.903	0.010	0.810	0.0225	0.723	0.040	0.640	0.0625	0.562
3	0.125×10^{-3}	0.857	0.1×10^{-2}	0.729	0.338×10^{-2}	0.614	0.8×10^{-2}	0.510	0.0156	0.422
4	0.625×10^{-5}	0.815	0.1×10^{-3}	0.656	0.506×10^{-3}	0.522	0.160×10^{-2}	0.410	0.391×10^{-2}	0.316
5	0.313×10^{-6}	0.774	0.1×10^{-4}	0.591	0.759×10^{-4}	0.444	0.320×10^{-3}	0.328	0.976×10^{-3}	0.247
6	0.156×10^{-7}	0.745	0.1×10^{-5}	0.531	0.114×10^{-4}	0.377	0.640×10^{-4}	0.262	0.244×10^{-3}	0.178
7	0.781×10^{-9}	0.698	0.1×10^{-6}	0.478	0.170×10^{-5}	0.320	0.128×10^{-4}	0.210	0.610×10^{-4}	0.133
8	0.391×10^{-10}	0.664	0.1×10^{-7}	0.431	0.256×10^{-6}	0.273	0.256×10^{-5}	0.168	0.152×10^{-4}	0.100
9	0.196×10^{-11}	0.631	0.1×10^{-8}	0.387	0.385×10^{-7}	0.232	0.512×10^{-6}	0.134	0.381×10^{-5}	0.0750
10	0.976×10^{-13}	0.599	0.1×10^{-9}	0.348	0.577×10^{-8}	0.197	0.105×10^{-6}	0.107	0.954×10^{-6}	0.0562
11	0.488×10^{-14}	0.568	0.1×10^{-10}	0.314	0.866×10^{-9}	0.167	0.205×10^{-7}	0.0859	0.237×10^{-6}	0.0422
12	0.245×10^{-15}	0.540	0.1×10^{-11}	0.282	0.130×10^{-9}	0.142	0.412×10^{-8}	0.0687	0.596×10^{-7}	0.0322
13	0.122×10^{-16}	0.513	0.1×10^{-12}	0.254	0.195×10^{-10}	0.121	0.825×10^{-9}	0.0595	0.149×10^{-7}	0.0237
14	0.612×10^{-18}	0.487	0.1×10^{-13}	0.229	0.294×10^{-11}	0.103	0.164×10^{-9}	0.0440	0.373×10^{-8}	0.0178
15	0.311×10^{-19}	0.466	0.1×10^{-14}	0.206	0.437×10^{-12}	0.0876	0.328×10^{-10}	0.0352	0.932×10^{-9}	0.0133
16	0.153×10^{-20}	0.440	0.1×10^{-15}	0.185	0.657×10^{-13}	0.0744	0.656×10^{-11}	0.0281	0.233×10^{-9}	0.0100
17	0.756×10^{-22}	0.418	0.1×10^{-16}	0.167	0.986×10^{-14}	0.0658	0.131×10^{-11}	0.0225	0.583×10^{-9}	0.750×10^{-2}
18	0.382×10^{-23}	0.397	0.1×10^{-17}	0.150	0.148×10^{-14}	0.0475	0.262×10^{-12}	0.0180	0.146×10^{-10}	0.562×10^{-2}
19	0.191×10^{-24}	0.377	0.1×10^{-18}	0.145	0.224×10^{-15}	0.0406	0.525×10^{-13}	0.0144	0.364×10^{-11}	0.422×10^{-2}
20	0.956×10^{-26}	0.368	0.1×10^{-19}	0.131	0.322×10^{-16}	0.0343	0.105×10^{-14}	0.0116	0.811×10^{-12}	0.322×10^{-2}

All of this assumes that the name-plate rating of a motor means what it says, which generally is not the case.

THE OPERATING FACTOR p

The factor p is here designated as the *operating factor* because it determines that part of the time the motor is actually operating. Similarly $(1 - p)$ determines that part of the time the motor is standing still. It is "dead time" when the driven machine is producing nothing. The higher the value of p, the more nearly continuous is the machine operation, the more the machine produces per day, and the less the overhead charges per unit of work accomplished. Every live factory manager spends much of his time in efforts to increase the value of p in his shop. By working the above method of computing resultant duty cycles backward, he can determine the existing average value of p from a curve-drawing instrument chart of input to his shop.

Let us say that $(1 - p)$ is a measure of the time when work is being removed from tools and being replaced. It is therefore a measure of man-power hours, just as p is a measure of horse-power hours. Roughly speaking, $p = 0.5$ means that half the time is spent in manual work.

Also the higher the value of p the more nearly constant is the load on the generating plant. Its efficiency is thereby increased. Fewer interruptions due to momentary excessive overloads will occur. The distributing system costs less per kilowatt-hour transmitted.

Appendix

The accompanying tables, giving values of p^r, $(1 - p)^{N-r}$ (Tables IV-1 and IV-2), and ${}^N C_r$ for values of N up to 20, (Tables V-1 and V-2), will be useful in applying (**4**), (**6**), and (**7**) from *Method of Calculation*.

For values of N greater than 20 the calculations of resultant duty cycles by the method given above

TABLE IV—2.
Values of p^r and $(1-p)^{N-r}$

r or (N − r)	p	(1 − p)	p	(1 − p)	p	(1 − p)	p	(1 − p)	p
	(1 − p)	p	(1 − p)	p	(1 − p)	p	(1 − p)	p	(1 − p)
1	0.30	0.70	0.35	0.65	0.40	0.60	0.45	0.55	0.50
2	0.090	0.490	0.122	0.422	0.160	0.360	0.205	0.303	0.250
3	0.0270	0.343	0.0429	0.275	0.0640	0.216	0.0912	0.166	0.1250
4	0.00810	0.240	0.0150	0.179	0.0262	0.130	0.0410	0.0915	0.06250
5	0.00243	0.168	0.525×10^{-2}	0.116	0.0102	0.0778	0.0185	0.0504	0.0313
6	0.729×10^{-3}	0.118	0.184×10^{-2}	0.0754	0.410×10^{-2}	0.0467	0.830×10^{-2}	0.0277	0.0156
7	0.219×10^{-3}	0.0823	0.643×10^{-3}	0.0490	0.164×10^{-2}	0.0280	0.374×10^{-2}	0.0152	0.781×10^{-2}
8	0.656×10^{-4}	0.0576	0.225×10^{-3}	0.0318	0.656×10^{-3}	0.0168	0.168×10^{-2}	0.838×10^{-2}	0.391×10^{-2}
9	0.197×10^{-4}	0.0403	0.788×10^{-4}	0.0207	0.262×10^{-3}	0.0101	0.758×10^{-3}	0.460×10^{-2}	0.195×10^{-2}
10	0.591×10^{-5}	0.0282	0.276×10^{-4}	0.0135	0.105×10^{-3}	0.604×10^{-2}	0.341×10^{-3}	0.253×10^{-2}	0.977×10^{-3}
11	0.177×10^{-5}	0.0197	0.965×10^{-5}	0.874×10^{-2}	0.420×10^{-4}	0.363×10^{-2}	0.153×10^{-3}	0.134×10^{-2}	0.488×10^{-3}
12	0.532×10^{-6}	0.0138	0.338×10^{-5}	0.568×10^{-2}	0.176×10^{-4}	0.218×10^{-2}	0.690×10^{-4}	0.766×10^{-3}	0.244×10^{-3}
13	0.159×10^{-6}	0.967×10^{-2}	0.118×10^{-5}	0.369×10^{-2}	0.706×10^{-5}	0.131×10^{-2}	0.310×10^{-4}	0.421×10^{-3}	0.122×10^{-3}
14	0.479×10^{-7}	0.676×10^{-2}	0.414×10^{-6}	0.240×10^{-2}	0.282×10^{-5}	0.783×10^{-3}	0.140×10^{-4}	0.232×10^{-3}	0.610×10^{-4}
15	0.144×10^{-7}	0.474×10^{-2}	0.145×10^{-6}	0.156×10^{-2}	0.113×10^{-5}	0.470×10^{-3}	0.628×10^{-5}	0.127×10^{-3}	0.305×10^{-4}
16	0.431×10^{-8}	0.332×10^{-2}	0.506×10^{-7}	0.101×10^{-2}	0.453×10^{-6}	0.282×10^{-3}	0.283×10^{-5}	0.700×10^{-4}	0.152×10^{-4}
17	0.129×10^{-8}	0.232×10^{-2}	0.175×10^{-7}	0.659×10^{-3}	0.181×10^{-6}	0.169×10^{-3}	0.127×10^{-5}	0.385×10^{-4}	0.763×10^{-5}
18	0.388×10^{-9}	0.163×10^{-2}	0.621×10^{-8}	0.428×10^{-3}	0.722×10^{-7}	0.102×10^{-3}	0.574×10^{-6}	0.212×10^{-4}	0.381×10^{-5}
19	0.116×10^{-9}	0.114×10^{-2}	0.217×10^{-8}	0.278×10^{-3}	0.288×10^{-7}	0.609×10^{-4}	0.258×10^{-6}	0.117×10^{-4}	0.141×10^{-5}
20	0.348×10^{-10}	0.796×10^{-3}	0.761×10^{-9}	0.181×10^{-3}	0.116×10^{-7}	0.365×10^{-4}	0.116×10^{-6}	0.640×10^{-5}	0.704×10^{-6}

become quite cumbersome, but in such cases the equivalent duty cycle curve (the H curves in Figs. 5 and 5A) approaches so nearly to a straight line that the demand frequency may be determined with sufficient accuracy by the method given in "Standardized Flexible Distributing Systems in Industrial Plants," *General Electric Review*, Vol. 21, p. 176-285. Indeed, this method may be used for values of N less than 20 if p is sufficiently large, say if $N\,p$ is 10 or more and if R is 1000 or more.

TABLE V—1.

Values of $^NC_r = \dfrac{N\,(N-1)\,(N-2)\,.\;.\;.\;.\;.\,(N-r+1)}{r\,(r-1)\,(r-2)\,.\;.\;.\;.\;.\,1.}$

r	$N = 3$	$N = 4$	$N = 5$	$N = 6$	$N = 7$	$N = 8$
1	3	4	5	6	7	8
2	3	6	10	15	24	28
3	1	4	10	20	35	56
4		1	5	15	35	70
5			1	6	24	56
6				1	7	28
7					1	8
8						1

r	$N = 9$	$N = 10$	$N = 11$	$N = 12$	$N = 13$	$N = 14$
1	9	10	11	12	13	14
2	36	45	55	66	78	91
3	84	120	165	220	286	364
4	126	210	330	495	715	1001
5	126	252	462	792	1278	2002
6	84	210	462	924	1716	3003
7	36	120	330	792	1716	3432
8	9	45	165	495	1278	3003
9	1	10	55	220	715	2002
10		1	11	66	286	1001
11			1	12	78	364
12				1	13	91
13					1	14
14						1

TABLE V—2.

Values of $^NC_r = \dfrac{N\,(N-1)\,(N-2)\,.\;.\;.\;.\;.\,(N-r+1)}{r\,(r-1)\,(r-2)\,.\;.\;.\;.\;.\,1}$

r	$N = 15$	$N = 16$	$N = 17$	$N = 18$	$N = 19$	$N = 20$
1	15	16	17	18	19	20
2	105	120	136	153	171	190
3	455	560	680	816	969	1140
4	1365	1820	2380	3060	3876	4845
5	3003	4368	6188	12816	11628	15504
6	5005	8008	12376	18564	27132	38760
7	6435	11440	19448	31824	50388	77520
8	6435	12870	24310	43758	75582	127970
9	5005	11440	24310	48620	92378	167951
10	3003	8008	19448	43758	92378	184756
11	1365	4368	12376	31824	75582	167951
12	455	1820	6188	18564	50388	127970
13	105	560	2380	12816	27132	77520
14	15	120	680	3060	11628	38760
15	1	16	136	816	3876	15504
16		1	17	153	969	4845
17			1	18	171	1140
18				1	19	190
19					1	20
20						1

Frequency tables (VI-1, VI-2, and VI-3) giving values of $^NC_r\,p^r\,(1-p)^{N-r}$ are included for $N = 5$, 10, 15, 20, and, in each case, for $p = 0.10$, 0.25, 0.50, 0.75, 0.90. From these typical group duty cycles for $P = 1.0$, $i = 1.0$ may be plotted and the correspond-

TABLE VI—1.

Frequency Tables: Values of $P_r = {}^NC_r\,p^r\,(1-p)^{N-r}$.

I. $N = 5$

r	$p = 0.10$	$p = 0.25$	$p = 0.50$	$p = 0.75$	$p = 0.90$
0	0.59	0.24	0.031	0.001	0.1×10^{-4}
1	0.330	0.400	0.155	0.014	0.45×10^{-3}
2	0.073	0.265	0.310	0.080	0.0081
3	0.0081	0.080	0.310	0.265	0.073
4	0.45×10^{-3}	0.014	0.155	0.400	0.330
5	0.1×10^{-4}	0.001	0.031	0.240	0.590

II. $N = 10$

r	$p = 0.10$	$p = 0.25$	$p = 0.50$	$p = 0.75$	$p = 0.90$
0	0.35	0.0575	0.001	0.1×10^{-4}	0.1×10^{-9}
1	0.390	0.19	0.010	0.3×10^{-4}	0.9×10^{-8}
2	0.194	0.286	0.044	0.4×10^{-3}	0.36×10^{-6}
3	0.0576	0.264	0.1175	0.3×10^{-2}	0.86×10^{-5}
4	0.0114	0.147	0.206	0.017	0.14×10^{-3}
5	0.15×10^{-2}	0.031	0.247	0.081	0.15×10^{-2}
6	0.14×10^{-3}	0.017	0.206	0.147	0.0114
7	0.86×10^{-5}	0.3×10^{-2}	0.1175	0.264	0.0576
8	0.36×10^{-6}	0.4×10^{-3}	0.044	0.286	0.194
9	0.9×10^{-8}	0.3×10^{-4}	0.010	0.192	0.390
10	0.1×10^{-9}	0.1×10^{-4}	0.001	0.0575	0.35

TABLE VI—2.

Frequency Tables: Values of $P_r = {}^NC_r\,p^r\,(1-p)^{N-r}$.

III. $N = 15$

r	$p = 0.10$	$p = 0.25$	$p = 0.50$	$p = 0.75$	$p = 0.90$
0	0.21	0.0135	0.3×10^{-4}	0.1×10^{-8}	0.1×10^{-15}
1	0.345	0.068	0.0005	0.4×10^{-7}	0.1×10^{-11}
2	0.268	0.164	0.003	0.9×10^{-6}	0.9×10^{-9}
3	0.132	0.232	0.014	0.1×10^{-4}	0.3×10^{-8}
4	0.044	0.233	0.043	0.1×10^{-3}	0.9×10^{-7}
5	0.011	0.174	0.093	0.7×10^{-3}	0.2×10^{-6}
6	0.002	0.095	0.155	0.004	0.3×10^{-5}
7	0.3×10^{-3}	0.041	0.120	0.014	0.3×10^{-4}
8	0.3×10^{-4}	0.014	0.120	0.041	0.28×10^{-3}
9	0.3×10^{-5}	0.004	0.155	0.095	0.002
10	0.2×10^{-6}	0.7×10^{-3}	0.093	0.174	0.011
11	0.9×10^{-7}	0.1×10^{-3}	0.043	0.232	0.044
12	0.3×10^{-8}	0.1×10^{-4}	0.014	0.232	0.132
13	0.9×10^{-9}	0.9×10^{-6}	0.003	0.164	0.268
14	0.1×10^{-11}	0.4×10^{-7}	0.5×10^{-3}	0.068	0.345
15	0.1×10^{-15}	0.1×10^{-8}	0.3×10^{-4}	0.014	0.210

TABLE VI—3.

Frequency Tables. Values of $P_r = {}^NC_r\,p^r\,(1-p)^{N-r}$.

IV. $N = 20$. (Values of P involving δ 0.10×10^{-5} and less omitted)

r	$p = 0.10$	$p = 0.25$	$p = 0.50$	$p = 0.75$	$p = 0.90$
0	0.13	0.32×10^{-2}	0.86×10^{-6}		
1	0.270	0.022	0.17×10^{-4}		
2	0.270	0.067	0.16×10^{-3}		
3	0.184	0.137	0.95×10^{-3}		
4	0.092	0.170	0.40×10^{-2}		
5	0.033	0.200	0.0126	0.36×10^{-5}	
6	0.89×10^{-2}	0.160	0.031	0.27×10^{-4}	
7	0.19×10^{-2}	0.116	0.062	0.15×10^{-3}	
8	0.36×10^{-3}	0.061	0.103	0.77×10^{-3}	
9	0.52×10^{-4}	0.027	0.136	0.32×10^{-2}	
10	0.65×10^{-5}	0.010	0.150	0.010	0.65×10^{-5}
11		0.32×10^{-2}	0.136	0.027	0.52×10^{-4}
12		0.77×10^{-3}	0.103	0.061	0.36×10^{-3}
13		0.15×10^{-3}	0.062	0.116	0.19×10^{-2}
14		0.27×10^{-4}	0.031	0.170	0.89×10^{-2}
15		0.36×10^{-5}	0.0126	0.210	0.033
16			0.40×10^{-2}	0.180	0.092
17			0.95×10^{-3}	0.137	0.184
18			0.16×10^{-3}	0.067	0.270
19			0.17×10^{-4}	0.022	0.270
20			0.86×10^{-6}	0.0032	0.130

ing H curves drawn for comparison with similarly grouped graphical instrument records (See Fig. 3A).

The following tables (VII-1, and VII-2) giving values of $p_r^{1/2}$ and $c\,p_s^{1/2}$, for various values of p_r, c, and p_s, within the ordinary range of duty cycles, may be useful in computing values of *duty cycle factors* (See section on Temperature Rating above).

TABLE VII—1.
Duty Cycle Factors

p_r = 0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09	
$p_r^{1/2}$ = 0.14	0.18	0.20	0.22	0.25	0.27	0.28	0.30	
p_r = 0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	
$p_r^{1/2}$ = 0.32	0.39	0.45	0.50	0.55	0.59	0.63	0.67	
p_r = 0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90
$p_r^{1/2}$ = 0.71	0.74	0.78	0.81	0.84	0.87	0.90	0.92	0.95

TABLE VII—2.
Duty Cycle Factors

C =	0.25	0.50	0.75	1.00	1.25	1.50
p_s	$c\,p_s^{1/2}$	$c\,p_s^{1/2}$	$c\,p_s^{1/2}$	$c\,p_s^{1/2}$	$c\,p_s^{1/2}$	$c\,p_s^{1/2}$
0.02	0.04	0.07	0.11	0.14	0.18	0.21
0.03	0.04	0.09	0.13	0.18	0.22	0.27
0.04	0.05	0.10	0.15	0.20	0.25	0.30
0.05	0.06	0.11	0.17	0.22	0.28	0.34
0.06	0.06	0.12	0.18	0.25	0.31	0.37
0.07	0.07	0.13	0.20	0.27	0.33	0.40
0.08	0.07	0.14	0.21	0.28	0.35	0.43
0.09	0.08	0.15	0.22	0.30	0.38	0.45
0.10	0.08	0.16	0.24	0.32	0.40	0.48
0.15	0.10	0.19	0.29	0.39	0.49	0.58
0.20	0.11	0.22	0.34	0.45	0.56	0.67
0.25	0.13	0.25	0.38	0.50	0.63	0.75
0.30	0.14	0.28	0.41	0.55	0.69	0.83
0.35	0.15	0.30	0.44	0.59	0.74	0.89
0.40	0.16	0.32	0.47	0.63	0.79	0.95
0.45	0.17	0.34	0.50	0.67	0.84	1.00
0.50	0.18	0.35	0.53	0.71	0.88	1.10

Thus if observation determines the values of p_r = 0.65, c = 0.75, and p_s = 0.15, then in Table VII-1 find $p_r^{1/2}$ = 0.81, and in Table VII-2, opposite p_s = 0.15, and under c = 0.75, find $c\,p_s^{1/2}$ = 0.29. The corresponding duty cycle factor is $d = 0.81 + 0.29 = 1.10$.

Discussion

V. Karapetoff: Let us take a machine shop, say with thirty identical machines, where thirty operators perform the same operation, for instance, turning a rod to a smaller diameter. Before each machine-tool raw parts are piled up, and when the whistle blows in the morning these men begin operations. Each one takes a piece, fastens it in the lathe, runs the cut, unfastens the piece and puts it back on another tray. Then he takes again another piece and performs the same operation. But all operators do not start at the same instant. Mr. Jones assumes that each machine is driven by an individual motor and as soon as the operation is completed the motor is stopped. Because the men do not start at the same instant, there is some phase displacement in the cycles, and Mr. Jones' problem is to evaluate, by the theory of probabilities, the demand on the power plant under those conditions.

In the case of a very large number of identical machines, the demand on the generating equipment cannot be very different from the average current; that is, if you superimpose those numerous duty cycles, you get practically a horizontal line. So that, in my estimation, with a large number of machines this whole complicated method of probabilities is unnecessary. Look at the tables in the paper. The coefficients in the binomial series are figured out to several places of decimals, to estimate the demand on a power plant. The author performs complete computations for the current, and shows in the end that according to the theory of probabilities the average current is 300 amperes. But the ordinary, common sense average is also exactly 300 amperes. Then, in another example, the difference between the current computed according to the formula of probabilities and the ordinary average is something like 2 amperes. One surely cannot estimate the equipment of an industrial plant down to 2 or 3 amperes.

On the other hand, let us assume that the number of motors is very small, for instance, in an office building with four elevators. Let it be required to estimate the curve of the power demand with any arbitrary time distribution of starting of these elevators. I doubt again, in this extreme case the advisability of applying the theory of probabilities. The theory of probabilities tells you what might happen with a large number of identical objects or events, the most probable combination is very likely to happen; but with only four objects such is not the case. It would not be safe to figure on the most probable curve of power demanded with four elevators starting at random. Now and then at least three of them may start at the same time, and even though this may not happen very often, it may mean an interruption of the service.

What we really want is not the most probable curve, but the danger curve of demand at starting; about this curve the theory of probabilities will give you no information whatever. Your ordinary common sense should tell you what to provide for. Thus, it seems as if we would have to eliminate from the scope of the paper both a large number of motors and a small number of motors.

The theory of probabilities is also not needed to compute the total kw-hr. per year. If I know the duty cycle of a motor, the number of such cycles per hour, and the number of machines, I can readily compute the total demand.

Mr. Jones computes separately the most probable current when a motor is running (with the starting rheostat out) and from it he determines the r. m. s. current for that part of the cycle; that is, the current that will give the same heating in the conductors as the actual current. Then he takes the starting period and figures out the r. m. s. starting current, over and above the running current. Finally he adds arithmetically those two r. m. s. currents; this last procedure is wrong. Since the heating is proportional to the square of the current, one cannot add effective currents arithmetically. It is necessary to take a square root of the sum of the squares. In the author's example, instead of a current of 507 amperes, I get only 372 amperes. However, when the theory of probabilities is used, it is not even permissible to take the sum of the squares; it is necessary to figure out the individual total currents, and to add their squares, each multiplied by the relative duration of time.

F. W. Owens: Mr. Jones' paper is a welcome innovation in the treatment of problems in electrical design. The introduction of new methods of attacking old problems is always stimulating and there is no doubt much more opportunity for the use in engineering practise of the methods of the theory of probabilities which have been of great service in the consideration of problems involving the treatment of mass data.

In applying new methods, however, the early attempts often lose sight of some of the niceties of the methods and may apparently lead to wrong results, or to a misinterpretation of results.

In the present paper of Mr. Jones, the problem considered, in essence, is that of designing the installation of generators and equipment, including protective devices, for furnishing current to a number of machines having regular duty cycles of known character, say a starting period drawing a heavy current, then an ordinary running period drawing less current, followed perhaps by an idle period. These characteristics of an individual machine being known, but the separate machines operating at random, it is necessary to estimate the amount of generating equipment and its character, and the nature and size of the various protective devices.

The *total* demand for current may readily be estimated without any elaborate methods, since it is simply the product of the average amount drawn by one machine and the number of machines.

More elaborate methods are necessary, however in considering such questions as the total size of generating plant and size of protective devices. Mr. Jones does not treat the first of these questions directly, although the methods of probabilities are very likely to be of much service there.

The most interesting part of Mr. Jones paper rests upon the following assumption which does not seem to be made sufficiently prominent. If a variable current flows in a circuit, the result is the same if the various periods in which the current has a given value are grouped together instead of occurring at different times. Mr. Jones uses this assumption only in regard to total input and heating effects. As far as total current is concerned, the assumption is obviously true. In the case of heating phenomena, it is true as far as the amount of heat produced is concerned, for this is proportional (for a circuit with fixed characteristics) to the square of the current multiplied by the time. However the disposal of this heat is vitally affected by the order in which the various sized currents flow, as well as their magnitudes, particularly if fuses, conduction of heat, etc., are concerned. I do not wish to discuss this phase of the matter, except to make clear the nature of the assumption, but this would have to be considered carefully.

In treating the question of "heat input" as well as total current input, Mr. Jones uses the concept familiar to the actuary as Mathematical Expectation. In applying this to the total input he proceeds correctly, although the complicated process is not necessary, but in his treatment of the heat input, or r. m. s. total input, he makes a serious error of principle, which I shall try to point out. The current input is divided into two parts in his argument, starting current and ordinary running current. These are treated independently, each as if the other were not present, and the results are added numerically. This leads to the correct result for the current itself, but to a wrong result except when only one size current is treated. I will first show this in a very simple problem, then in the illustration Mr. Jones uses in his paper.

Consider two machines each with the following duty cycle. The machine uses 200 amperes for one second, then 100 amperes for three seconds, then is idle for two seconds, then repeats. For each machine, at any time, the probability that it is starting is 1/6, that it is running light is 3/6, and that it is idle is 2/6. Thinking of the starting currents and running currents as distinct, we would say with Mr. Jones that the probability that a machine is running is 4/6, that it is idle is 2/6. We would then have a probability (4/6) (4/6) = 16/36 that both machines are running, 2 (4/6) (2/6) = 16/36 that one machine is running and that the other is idle, (2/6) (2/6) = 4/36 that both machines are idle. The respective currents flowing are 200, 100 and 0 amperes. For the root mean square running current we would have

$$\sqrt{\frac{16}{36}(200)^2+\frac{16}{36}(100)^2+\frac{4}{36}(0)} = 149 \text{ amperes}$$

For the starting currents, thought of as extra currents, for each machine the probability of extra current flowing is 1/6, the probability of its not flowing is 5/6. The probability that both machines have extra current flowing is (1/6) (1/6) = 1/36. The probability that extra current is flowing in one machine and no extra current in the other is 2 (1/6) (5/6) = 10/36. The probability that neither machine is drawing extra current is (5/6) (5/6) = 25/36. The total amount of extra current drawn in the three cases is 200, 100 and 0 amperes, respectively. We have then for the r. m. s. of the extra starting current

$$\sqrt{\frac{1}{36}(200)^2+\frac{10}{36}(100)^2+\frac{25}{36}(0)} = 62 \text{ amperes}$$

Adding, we would have for total r. m. s. current 149 plus 62 = 211 amperes, which is the result of following Mr. Jones' process.

The correct procedure is as follows, since there is no distinction between ordinary running current and starting currents, and the *sum* should be squared, rather than treating the results separately. There are six different possibilities, according to what the motors are doing. If we use $(a\ b\ c)$ to mean a motors are starting, b motors are running steadily, c motors idle, these cases are (2 0 0), (0 2 0), (0 0 2), (1 1 0), (1 0 1), (0 1 1). The respective probabilities are (1/6) (1/6), (3/6) (3/6), (2/6) (2/6), 2 (1/6) (3/6), 2 (1/6) (2/6), 2 (2/6) (3/6). The respective currents are 400, 200, 0, 300, 200, 100 amperes. Hence for the root mean square input we should have

$$\sqrt{\frac{1}{36}(400)^2+\frac{9}{36}(200)^2+\left(\frac{4}{36}\right)(0)+\frac{6}{36}(300)^2+\frac{4}{36}(200)^2+\frac{12}{36}(100)^2} = 193 \text{ amperes}$$

instead of the 211 amperes obtained by the wrong process.

In general, if we have N machines, each with a probability p_1 of a current i_1, probability p_2 of a current i_2, . . . probability p_n of a current i_n, the probability of any given combination of k_1 machines drawing a current i_1, k_2 machines drawing current i_2, etc., is obtained from the term containing $p_1^{k1}\, p_2^{k2}\, p_3^{k3}$ . . . in the expansion of $(p_1 + p_2 + p_3 + \ldots p_n)^n$.
(See Hall and Knight, Higher Algebra, or any standard book on Probabilities).

If we apply this to the problem given by Mr. Jones, in which we have six machines each with a duty cycle of 20 seconds, using 200 amperes for 5 seconds, then 100 amperes for 5 seconds, then idle 10 seconds, the work may be tabulated as follows:

Number of motors drawing			$p = 1/4$, $q = 1/4$, $r = 1/2$ Probability π of the combination	Current $\frac{i}{100}$	$\frac{i^2}{10,000}$	$\frac{4^6\,(\pi\, i^2)}{10,000}$
200	100	0				
6	0	0	$p^6 = 1/4^6$	12	144	144
5	1	0	$6\,p^5 q = 6/4^6$	11	121	726
4	2	0	$15\,p^4 q^2 = 15/4^6$	10	100	1500
3	3	0	$20\,p^3 q^3 = 20/4^6$	9	81	1620
2	4	0	$15\,p^2 q^4 = 15/4^6$	8	64	960
1	5	0	$6\,p\,q^5 = 6/4^6$	7	49	294
0	6	0	$q^6 = 1/4^6$	6	36	36
5	0	1	$6\,p^5 r = 12/4^6$	10	100	1200
4	1	1	$30\,p^4 q\,r = 60/4^6$	9	81	4860
3	2	1	$60\,p^3 q^2 r = 120/4^6$	8	64	7680
2	3	1	$60\,p^2 q^3 r = 120/4^6$	7	49	5880
1	4	1	$30\,p\,q^4 r = 60/4^6$	6	36	2160
0	5	1	$6\,q^5 r = 12/4^6$	5	25	300
4	0	2	$15\,p^4 r^2 = 60/4^6$	8	64	3840
3	1	2	$60\,p^3 q\,r^2 = 240/4^6$	7	49	11,760
2	2	2	$90\,p^2 q^2 r^2 = 360/4^6$	6	36	12,960
1	3	2	$60\,p\,q^3 r^2 = 240/4^6$	5	25	6000
0	4	2	$15\,q^4 r^2 = 60/4^6$	4	16	960
3	0	3	$20\,p^3 r^3 = 160/4^6$	6	36	5760
2	1	3	$60\,p^2 q\,r^3 = 480/4^6$	5	25	12,000
1	2	3	$60\,p\,q^2 r^3 = 480/4^6$	4	16	7680
0	3	3	$20\,q^3 r^3 = 160/4^6$	3	9	1440
2	0	4	$15\,p^2 r^4 = 240/4^6$	4	16	3840
1	1	4	$30\,p\,q\,r^4 = 480/4^6$	3	9	4320
0	2	4	$15\,p\,q^2 r^4 = 240/4^6$	2	4	960
1	0	5	$6\,p\,r^5 = 192/4^6$	2	4	768
0	1	5	$6\,q\,r^5 = 192/4^6$	1	1	192
0	0	6	$r^6 = 64/4^6$	0	0	0
						99,840

For root-mean-square current we have

$$\sqrt{\left(\frac{99,840}{4^6}\right)(10,000)} = 493.+$$

By Mr. Jones' method, the result was 507 amperes instead of the correct 493—remarkably close for a faulty process.

It is obvious that the numerical computations become rapidly more difficult as the number of machines, or number of different sized currents is increased. The tables in Mr. Jones paper do not help in this as they are of no value when the number of currents not zero is two or more.

It should further be remarked that those unfamiliar with the subject of probabilities should be careful not to understand that Mr. Jones means actually to predict what currents will really flow in the circuits involved at any time, but that the figures are to be understood as averages to be expected. Neither the theory of probabilities nor any thing else can predict the actual happenings, except in this sense of averages, although it can state what is most likely to happen, and the degree of probability of either the most likely, or some other, occurrence.

Bassett Jones: I regret that the error pointed out by V. Karapetoff and F. W. Owens exists in the method. The same error has been recently pointed out to me from two other sources, also with the remark that the error in result is small. As a matter of fact this error has not been picked up in any actual case while the method has been in use during the past several years. In other words, measured results have always compared so closely with calculated results that no reason for doubt developed.

The method has its limits, of course, but a method with limits is better than no method at all. Probabilities is merely a way of guessing intelligently. By its use, guesses have proved to be nearly correct. Without it, the margin of deviation between the guess and the actuality in many cases, has proved to be considerable.

The necessary correction is quite obvious. It is in the approximation used (See Figs. 1 and 2.) The running current i should be taken for the time T_r-T_s'. The starting current, I_m, and *not* $I_r = I_m - i$, should be taken for the time T_s'. In Fig. 3, take i for the time $T_r - T_s$, I_s for the time T_s, and I_m for the time T_s'. In other words, the proper divisions of the duty cycles are vertical, *not* horizontal.

Then, in Fig. 1, $p_r = T_r - T'_s/T$, $p_s = T_s'/T$, and similarly for Figs 2, and 3.

The calculations performed exactly as directed with these changes, give the corrent r. m. s. values. The average values are the same with the correct and the incorrect method.

I am sorry that Mr. Karapetoff's doubts as to the value of the method as a whole are not borne out by actual experience. It has been used to determine the probable average, and probable frequency and amount of peaks for four elevators. We have not heard of any shut-downs due to the wrong selection of either fuses or circuit breakers. It has been used to determine the load distribution for 20 elevators—not all of the same capacity, nor on the same service. Here again, no shutdowns have been reported. And because the method proved useful in this case, the tables were included up to $n = 20$.

I believe the method, as applied to averages, is used in life insurance when n considerably exceeds 20, say a million or more, and many millions of dollars are invested accordingly. Surely the probable starting and stopping of a motor is a certainty compared to the probable period of a man's life.

This does not mean that the method should be used when n is large. Then the more approximate method given by me in "Standardized Flexible Distributing Systems in Industrial Plants" is available, all as pointed out in the paper.

Let me add that the description of the method looks more complicated than it actually turns out to be in practise. Much of it can be graphed for ready reference.

Queenston-Chippewa Development of the Hydro-Electric Power Commission of Ontario

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Review of the Subject.*—This paper covers a general description of the entire Queenston-Chippewa development of the Hydro-Electric Power Commission of Ontario, on the Canadian side of the Niagara River, which will have an ultimate capacity approximating 650,000 h. p.*

The general scheme of the development comprises an intake structure in the Niagara River at Chippewa; the utilization, by deepening and widening, of the Welland River as a part of the waterway for 4½ miles; the construction of a canal 8½ miles long from the Welland River to the forebay and screen house on the top of the Niagara escarpment about a mile south of Queenston village; and the construction and equipment of the power house in the gorge immediately below the forebay.

The entire design was carried out with the express object of producing power most efficiently from the available water at the lowest possible cost.

Important features of the waterway are described, covering the special design of intake works to avoid ice troubles; the control gate in the canal; the concrete lined canal channel, and the consideration given the design of canal, forebay, screen house, penstocks and draft tubes to obtain the best hydraulic results.

Of special interest to hydroelectric engineers is the use of the largest capacity turbines and vertical shaft generators that have ever been constructed; the size of the step-up transformers; the design and arrangement of relay systems and of switching equipment to take care of the extremely heavy short-circuit conditions; and features of the design of the power house whereby in every 50-foot length of building all equipment for one 45,000-kv-a. unit, covering penstock, turbine, generator, switching equipment, transformers and outgoing line, is accommodated; the provision of the main floor in the generator room at the top of the generator frame; also the use of a control pedestal on main floor at each unit whereby the turbine and generator may be conveniently operated.

Power for the plant service equipment is obtained from two separate small units, entirely independent of the main units, and 25-cycle current is used exclusively for service equipment motors, including the 300-ton crane equipment and the elevators.

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It is the intent of this paper to give an outline only of the engineering features involved in the undertaking. Under the term "Development" is included only the plant involved in supplying power to the 12-kv. busses, but as the transformer station is combined with the generating station the paper will deal with both features.

Throughout the period of preliminary study of the development and later as the design progressed, continuous use was made of models of the various structures in order that the mathematical analysis might be reinforced by actual demonstrations under the assumed conditions. Such models were made for the studies of the intake, the bends in the canal, the transitions, the diffuser at the mouth of the forebay, and on the draft tubes and station substructure. A calculation table for determining short-circuit conditions was also developed. It is believed that the beneficial result of such studies and of the care taken in the design of what are often considered minor elements of a power development will be demonstrated when complete test results are available.

Such tests as have already been made indicate conclusively that at least as high an over-all efficiency from head water to tailwater has been secured, as has ever before been obtained.

True conservation in the use of the waters of the Niagara River for power purposes demands that practically the whole fall of approximately 327 feet between Lake Erie and Lake Ontario be utilized. The various power plants now operating at Niagara Falls vary in head from 130 feet to 210 feet, and with widely different degrees of efficiency.

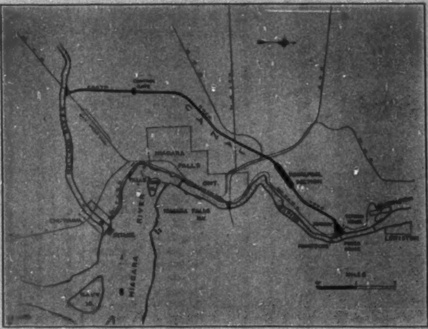

Fig. 1—Map of the Development

The Queenston-Chippewa power development, the first unit of which was operated first in December 1921,

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Presented at the Annual Convention of the A. I. E. E. Niagara Falls, Ont., June 26-30, 1922.

will have a normal operating head of 305 feet when the installation is complete. The conservation of head effected by the reduction of hydraulic losses to a minimum, and by refinements in the design of the various essential elements of the project as a whole, has resulted in the production of a power development which is believed to represent the best in modern engineering practise.

The plant in operation and in course of construction will consist of five 45,000 kv-a., 187.5 rev. per min. units, generating power at 12 kv., three-phase, 25 cycles, which in turn is transformed to 110 kv. for transmission. Ultimately the plant will consist of nine or ten units, with an ultimate capacity of 575,000-650,000 horse power. The subsequent units in all probability will have greater capacity than those being installed at present. Two of the units are now in service developing 110,000 horse power, which is being delivered to the existing 110-kv. system at Niagara Falls for transmission to Toronto, London and Windsor (opposite Detroit), Sarnia and intermediate municipalities.

A glance at the accompanying map, Fig. 1, will indicate the relation of the various works comprising the development. Water is taken from the Niagara River about one mile above the Falls, is conveyed through the improved section of the Welland River, a distance of 4½ miles, thence by a canal 8½ miles long, to the forebay and screen house located on the Niagara River about one mile south of the village of Queenston. From the screen house, steel penstocks encased in concrete carry the water down the cliff to the power house, from which it passes to the Niagara River.

Construction work was carried on almost exclusively by an electrically driven plant, the electrical load at times being in the neighborhood of 20,000 horse power.

INTAKE

On the Niagara River one of the great obstacles to securing continuity of service is the annual formation and flow of ice. Great fields of ice, formed in Lake Erie with its shallow bays and shores, are discharged down the Niagara River every spring, and at frequent intervals during the winter, under the proper coincident wind and temperature conditions. The river itself develops considerable anchor and frazi-ice at times of low temperature, but it never freezes over.

The site of the intake of the Queenston-Chippewa power development, at the mouth of the Welland River is favorable in that floating ice in the Niagara River does not ordinarily follow the shore lines at this point; but the smooth gradient of the river surface and the comparatively shallow water with its low velocity is unfavorable.

The removal of water in large quantities from a river heavily charged with ice is always a difficult problem, but is much simplified when a natural break in the river surface, accompanied by a sudden drop, gives a source of power for the separation of floating ice, and for its continuous disposal. The use of a horizontal diaphragm to skim the surface water with its burden of ice from the lower strata, thus permitting the upper layer to be accelerated and removed clear of the intake without objectionable eddies, while the lower layer clear of all ice is changed in direction and flows through the intake into its new channel, gives a positive and satisfactory solution.

When the natural conditions do not permit such an arrangement, as in the present case, radically different measures must be taken. To confirm certain ideas developed as a result of many years' experience and observation of the Commission's engineers, on the present plants operating on the Niagara River, an extended series of tests and experiments on large-size models were made, these models duplicating to scale the topographical conditions existing at the site of the intake. The result of these experiments contributed to the preparation of a design which, it is confidently expected, will operate in such a way as to keep the plant wholly free of this ice menace.

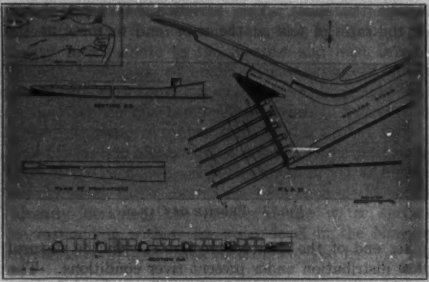

FIG. 2—INTAKE

The illustration of the intake, Fig. 2, shows clearly the physical nature of the design. The complete intake structure is approximately 1100 feet in length and is made up of an entrance with lock gates for navigation, a bulkhead section, and the intake proper, the latter combining two forms of intake; the conventional or surface intake consisting of a concrete barrier or boom with fifteen openings each 18 feet in width, normally having eight feet of submergence, which submergence can be increased however by means of drop gates, to any amount up to the full depth of water or 35 feet; and the submerged intake consisting of gathering tubes or draft distributors, six in number and 675 feet in length. Water enters the tubes along a distance of 500 feet through a slot on their upstream sides. These tubes are controlled by gates similar to those on the surface intake, and comprise an outer tapering section, wherein the velocity is maintained constant, with a longer inner section of twenty-foot diameter, wherein the velocity regularly increases with respect to distance along its axis. Diffuser sections are situated at the inner end to reduce the velocity to that existing in the Welland River section with as little loss as possible.

The slot on the upstream side of the tubes varies in width from one foot at the shore end to four feet at the outer end, where the slot ends. A restricted section, shaped somewhat like a bathtub, forms a mouthpiece for each tube, its function being to give the required initial impulse to the sucking slot.

The head at any point on the tube, causing flow through the slot, is the resultant of three components (a) the initial loss due to the primer, (b) the total of the induced losses due to the increments of angular flow through the slot, and (c) the total cumulative friction head loss in the tube, including velocity head.

The designed rate of total inflow through each slot is 2500 cubic feet per second along the axis of the tube. The rate of inflow per running foot of slot has not been chosen uniform, however, because the river naturally feeds more water at the outer end of the tubes than nearer the shore. This variation has been chosen in the ratio of four at the outer end to three at the inner end of the slot, which agrees with the natural flow distribution under present river conditions. The total head loss in each gathering tube to the end of the diffuser, with a flow of 2500 cu. ft. per sec. in each tube, will be only three-tenths of a foot.

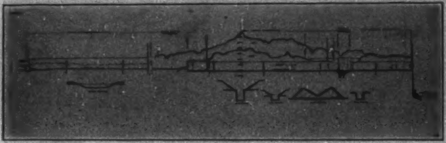
FIG. 3—PROFILE OF CANAL

During the greater part of the year, when no ice is running in the river, the intake gates of both surface and submerged intakes will be open. The navigation channel will also be open and the velocity through the intake at any point will therefore, be very low, so that the head loss under ordinary conditions will be negligible.

THE CANAL

For a great many miles above its mouth the Welland River is a sluggish stream, meandering slightly in a depression that can hardly be called a valley. This stream for four and a half miles forms the first reach of the canal, and its low banks provided a suitable disposal area for much of the material excavated in the process of straightening and deepening the channel. The radius of curvature of some of the bends is increased in the new alinement, but in the main the old channel location is followed. The velocity under full-load conditions will be low, being limited by the scouring velocity for the clay soil through which the improved channel is cut. The canal leaves the river channel near the crossing of the Michigan Central Railway and turning through a deflection of 28 degrees takes a course almost due north for over three miles. The ground surface (Fig. 3) rises fairly uniformly until the crossing of Lundy's Lane is reached. The elevation here is over 660 feet above sea level or 100 feet above the water surface of the intake. The earth overburden is quite heavy (Fig. 4) for the whole of this portion of the canal, the bottom grade of the canal cutting the rock surface one mile from the Welland River. The maximum rock elevation which is 604, is beyond Lundy's Lane and therefore not coincident with the maximum earth surface elevation but the profiles of rock and earth surface are roughly parallel to each other. Just beyond Lundy's Lane there is the maximum bend with a deflection of 51 degrees,

FIG. 4—CANAL IN ROCK SECTION

FIG. 5—CANAL SHOWING BRIDGES

and at intervals of a little over a mile each, two other bends of 27 and 31 degrees. The earth over-burden continues fairly uniform (Fig. 5) for three miles beyond Lundy's Lane until Bowman's Ravine is reached. Here, both rock and earth surfaces fall sharply to an elevation far below the grade of the finished canal. The ravine here is apparently an old river channel through which the Niagara River in preglacial times flowed toward Lake Ontario. At the time the construction started this was the course of a small stream having its outlet at the Whirlpool. The ravine crossing, Fig. 6, is made on a fill and the ravine itself proved a convenient disposal area for about 1,500,000 cubic yards of excavated material.

FIG. 6—LOOKING NORTH— CANAL AT WHIRLPOOL SECTION

Where the canal section again enters the rock cutting beyond the ravine, the earth over-burden becomes very light, in some places amounting to only a foot or so. Two deflections are made in the remaining two miles of the canal, one of 33 and one of 47 degrees. A quarter mile beyond the second of these curves the forebay (Fig. 7) is reached.

The Design of the Earth and Rock Sections. Long continued investigations were made of available information on roughness factors for large canals in earth and rock with and without concrete lining. One of the conclusions reached was that Kutter's formula should be used. The roughness factors used in the hydraulic studies were 0.035 for the river section and 0.012 for the concrete lined rock section.

Forty-eight hundred feet from the Welland River the rock surface cuts the bottom grade of the canal. The shape and size of the channel begins to change here, a transition to the rectangular cross-section of the rock section taking place.

A thorough study of excavating machinery and methods that was carried on in 1916 and 1917, indicated the economy of using heavy equipment capable of loading the spoil from the bottom of the cut into cars at the surface. A cut at least forty-eight feet in width was necessary to permit these large shovels to work and economy studies indicated that the saving effected by the large shovels would compensate for any other losses that the wide cut occasioned.

Economy Studies. The procedure in determining the economic proportions of the canal will be outlined briefly. It is essential that the canal should carry full quantity of water required under the lowest conditions of water level in the Niagara River. A series of canals was designed each of forty-eight-foot width and capable of carrying the required supply of water with uniform flow and with low water in the Niagara River at Chippewa. The first of the series was of such a depth that the velocity would be four feet per second and the designed slope of the bottom and water surface was the requisite slope for uniform flow, the others being designed for higher velocities.

The cost of each of these canals was figured and a curve plotted between low water velocity and cost. From this curve the tangents were scaled for various low water velocities. For low velocity the canals will be deep and therefore costly. For very high velocities the canals will be shallow but the slope so steep that the cost will be greater than for moderate velocities, the canal of minimum cost being for a velocity intermediate to the greatest and least investigated. The canal of minimum cost, however, is not necessarily the most economical. Enlargement will reduce the friction loss and consequently increase the head and power output at a cost which up to a certain point is both justifiable and economic. The determination of the economic size is based not on low water but on the mean water conditions. For each of the canals already designed, the profile of the water surface corresponding with mean water level in the Niagara River is computed, thus determining the friction loss and lost power at mean water. Tangents were scaled from a lost power curve plotted from these results and were divided into the tangents from the lost power curves for each low water velocity. The dividend in each case is the cost in dollars per horse power of

FIG. 7—VIEW OF FOREBAY AND POWER HOUSE

the power gain at the particular velocity to which the result applies. These dividends are now plotted against low water velocity, constituting an "economy curve" from which the economic velocity may be selected.

Slight changes in the head give increases in power without appreciable change in operating or maintenance costs, and the only essential charge against power gained by slight enlargements of the canal is the interest charge on the cost of enlargement. The economic velocity, therefore, is one corresponding with the total cost per horse power on the economy curve considerably higher than the total average cost of the whole development.

Control Works. A control gate (Fig. 8) is located at station 97+00 which is near the beginning of the rock section. This is an electrically operated Stony sluice of forty-eight foot clear span, the full width of the rock section. The use of two gates with a central pier was considered, but the single gate was found to be the most advantageous, as it provided an unobstructed waterway with a consequent reduction in friction losses. The gate, which is supported on steel towers with a concrete substructure, weighs approximately 100 tons, and is provided with two hoisting mechanisms and two counterweights. The gate when at the top of its run is sufficiently above the water surface in the canal to permit a tug to pass beneath.

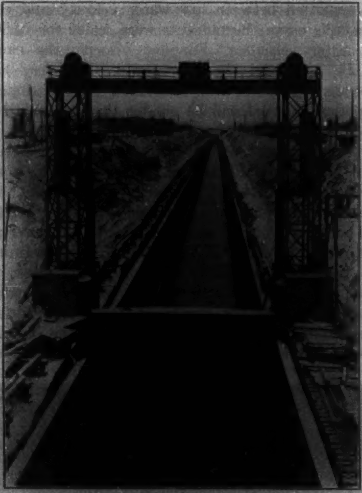

FIG. 8—CONTROL GATE

Whirlpool Section. Bowman's Ravine west of the whirlpool was crossed on a rock fill, the cross-section of the canal being changed from a forty-eight-foot rectangular section to a trapezoidal section with ten-foot bottom width and side slopes of one vertical and one-half-to-one horizontal. This cross-section was designed to be as large as the rock section at the extreme minimum water level at which operation of the generating station could take place, and of course, the trapezoidal shape gives it greater area than the rectangular for any water surface elevation greater than this. The whirlpool section is lined with concrete, carrying considerable reinforcement to protect the lining, in the event of settlement of the fill. It was also anticipated that should the canal be emptied at any future time, this lining would not withstand the inward pressure of the water with which the supporting rock fill would be saturated, so vents of sufficient size to drain the fill as quickly as the water could be drawn down in the canal, were provided near the top and bottom of the channel. These vents are protected with light wooden covers, which will be dislodged under a comparatively small excess of inward pressure.

Concrete Lining. Economic considerations prompted the lining of the canal with concrete. The height of the lining was fixed slightly lower than the profile of the water surface existing when the load conditions on the plant are a maximum and the Niagara River flow is a minimum. Thus, at all times the lining will be protected by submergence against the action of frost. The thickness of the lining varied with the rock over-break but averaged about 20 inches, and where necessary, steel dowels were used to anchor the concrete lining to the rock face.

It was held that extreme smoothness of surface was not the only determining factor, but that precise alinement is also a most important element in the reduction of hydraulic losses. Great care was taken to obtain a smooth surface by the use of steel forms, and a positive and rigid method of form setting was devised, which insured almost perfect alinement. The results obtained were very excellent, and it is expected that when opportunity offers to test experimentally the efficiency of lined section of the waterway, extremely low roughness factors will be realized.

The Forebay. The kinetic energy of the water at the end of the canal, and at entrance to the forebay was too great to neglect in the design. Necessarily, in the forebay the velocity of the water will be so greatly reduced as to make its velocity head negligible, and some means therefore had to be found to regain the energy in the water as its velocity decreased. The same difficulty is experienced here as in any transition in which velocity is being reduced, namely, that the stream lines tend to follow paths of their own course, unless the design is very carefully worked out and the angle of divergence properly fixed.

A great mass of experimental data on diverging tubes for air and water is available, indicating that a ten-degree angle of flare is the most efficient. In order to confirm for this particular case the conclusions arrived at from other experiments, a model of the forebay was built in the Hydraulic Laboratory of the University of Toronto, and tried out with nineteen transitions of various angles and lengths. These experiments confirmed the conclusions reached from other available data, and also provided, in their quantitative results, a basis for the economic design of a transition that would cost no more than was justified by the gain in power from reclaimed head. These experiments involved measurements of extremely small differences of water level, necessitating observations to thousandths of an inch as the velocities in the model were quite low—only one-twelfth of the corresponding velocity in the full-size structure. Notwithstanding this condition, the results were, with very few exceptions, quite consistent and resulted in the design of the "diffuser" structure inserted in the forebay transition, providing two entrance passages into the forebay, each with a diverging angle of ten degrees (Fig. 9). It consists of a wedge-shaped structure 221 feet long and 37 feet wide at the downstream end. The sides are vertical, straight and smooth and are carried 28 feet above the bottom of the forebay. An opening 16 feet by 20 feet in the end wall assures approximately equal pressures on both sides of the walls.

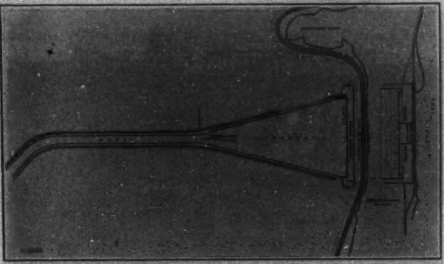

FIG. 9—GENERAL PLAN OF FOREBAY AND POWER HOUSE

Through this expedient, the high velocity at the end of the canal is gradually reduced and its kinetic energy recovered, with the result that the elevation of the water in the forebay beyond the deflector will be higher than at the mouth of the canal. For a flow of 15,000 cubic feet per second, and mean water level at Chippewa, the reclaimed head amounts to approximately one foot.

SCREEN HOUSE

At the lower end of the forebay, and serving as a dam for the same, is located the screen house. This structure forms the entrance, and the control, for the penstocks. The entrance to each of the main penstocks is a modified bellmouth consisting of three openings 12 feet 8 inches wide and 29 feet high at the rack supports. These three openings gradually converge into one opening 16 feet in diameter at the point of connection to the penstocks. In designing these water passages particular care was given to the securing of smooth stream lines and consistent changes in velocity. The bell-mouth entrances are sealed by a concrete curtain wall extending down to elevation 542.0 which gives a depth of 28 feet above the floor of the forebay. Immediately behind the curtain wall, steel-lined gate checks are provided to support structural steel gates. These provide a means of unwatering in case it is necessary to get at the lower sections of the racks, or for inspection of the penstocks. The dividing of the intake into three waterways was done in order that the spans for the gates could be made of convenient size and to permit the use of racks of a somewhat new design. The racks, which consist of three-inch by three-eighths-inch bars on edge, at five-inch centers, are fastened rigidly to a structural steel supporting frame held in checks in the concrete walls. The whole of the rack structure is removable and they are split horizontally into two sections for convenience in handling. A specially designed rack follower with an automatic latch arrangement is provided to facilitate the removal of the racks, the bottom section being a considerable distance below the floor of the screen house. The bars and the supporting structure of the racks are designed to withstand a head of 10 feet with a stress of 20,000 pounds to the square inch in the steel. This type of construction removes the danger of a serious shutdown due to the collapse of rack structures, as in the event of blocking by ice or other foreign matter the failure of one section would immediately relieve the others. The broken section can then readily be replaced with a spare one without serious interruption to operation.

A trash trench of liberal dimensions extends across the bottom of the forebay immediately in front of the screen house piers to collect any debris or foreign material which may travel along the bottom of the forebay. The piers dividing the main unit entrances are 6 feet in thickness, while the two intermediate piers in each unit are 3 feet thick. The main dividing piers are designed for full water pressure on each side in order that any unit of the intake may be unwatered while the adjacent units are in operation. An opening in the main floor immediately behind the racks provides a means of disposal of trash into a trough, which empties into the ice chute.

The screen house, as constructed, provides for nine main units, a service unit and an ice chute, and is arranged so that a further unit entrance may be added at the north end.

The entrance to the service unit is similar to the main unit, except that it consists of one bay only, and the entrance to the penstock itself is a true bell-mouth instead of the sectionalized transitions in the main unit entrances. The ice chute bay has a clear width of 25 feet and is provided with a sluice gate of the Stony type, which is lowered to pass surface water carrying ice. After passing the gate, the water and ice enter a 10-foot diameter concrete pipe and passing down the cliff, out beneath the power house, empty into the Niagara River. Stop log checks are provided ahead of the gate for use in an emergency, or for inspection purposes.

The screen house is located close to the edge of the escarpment, only a narrow ledge of rock being left between it and the gorge. Owing to the disastrous results which would follow a failure, the screen house substructure was designed to resist the full head exerted by the water in the forebay without any assistance from the adjacent rock. The superstructure is built with reinforced concrete walls and roof with a structural steel framework, and is equipped with an electrically operated traveling crane of 25-ton capacity for handling the racks and gates. At the south end of the screen house proper, an enlargement of the building provides for administration offices, and entrance to elevator to the tunnel giving access to the generating station.

PENSTOCKS

From the screen house, the water is carried to the turbines in steel plate penstocks. The main unit penstocks are 16 feet in diameter for approximately two-thirds of their length, and are then reduced by a taper section to a diameter of 14 feet. The accompanying illustrations show the excellent alinement of the penstocks, there being only two bends, one located at the top and one at the bottom. These elbows are held in massive concrete anchor blocks, the one at the upper bend forming a foundation for the piers supporting the sidewalk and roadway along the edge of the escarpment.

Each penstock ring is made up of two plates with longitudinal joints on the horizontal center line. These joints are all double butt joints, varying from double riveted at the top to quadruple riveted at the lower end. The circumferential joints are also single butt, double riveted with the butt strap on the outside. The longitudinal joints are calked on the inside, but the circumferential joints are made water-tight by electric welding. This type of circumferential joint gives a very much better alinement to the inside of the pipe than can be obtained with the usual outside and inside course with lap joints. In designing the penstocks a stress of 12,000 pounds to the square inch was used, this figure being taken to provide for the exigencies of corrosion, fatigue, suddenly applied loads, and other indeterminate or unknown contingencies. The internal pressure, used for design purposes, was taken to be the static head, plus the pressure rise due to a complete closing of the turbine gates in 1½ seconds. This increase in pressure was taken as a maximum at the turbine gates and varying uniformly to zero at the racks.

The thickness of the plates varies from one-half inch at the top section to one and one-quarter inches at the lower section, while the longitudinal butt straps are one-half inch thick with two rows of seven-eighths inch rivets for the lightest joint, and fifteen-sixteenths-inch thick with four rows of one and three-eighths-inch rivets for the heaviest. The efficiency of the longitudinal joints at the heavy section is approximately 85 per cent. In the erection of the penstock, a new departure was initiated in the use of electric rivet heaters; by this method a consistent and close range of temperature was possible so that burnt rivets were very rarely encountered.

The penstocks are covered throughout their entire length with a concrete envelope, having a minimum thickness of 24 inches, which protection will, it is believed, greatly increase the life of the steel pipes.

The penstock for the service units follows the same alinement as the main penstocks and has a diameter of five feet. As friction loss in this pipe was not such an important factor, lap joints and inside and outside courses were used.

GENERATING AND TRANSFORMER STATION

The generating and transformer station (Fig. 10) is located below the escarpment and close to the River's edge. As will be observed from the cross-section drawing, the station extends about one-half the distance to the top of the escarpment. The structure required to house five main units and the service equipment is 350 feet long, and ultimately this length will be doubled. The substructure is of massive concrete construction carried down to rock foundations, and provides chambers and tunnels for housing and giving access to various kinds of apparatus. The superstructure consists of a structural steel frame work with reinforced concrete floors and roofs, and concrete, brick and tile walls and partitions.

FIG. 10—VIEW OF POWER HOUSE
From American side of river.

The location of the transformer and switching portion of the plant on the top of the escarpment was considered, but owing to the difficulties in carrying the current at 12 kv. from the generators to the transformers up the cliff; and to operating advantages in having a combined station; also to the space between the generator room and the cliff being sufficient for the purpose, the decision was made to have the building to house the transformers and switching equipment combined with the generator room. It will be noted from the cross-section of the plant (Fig. 10A) that the layout of electrical equipment accommodates itself to the 60-degree slope of the cliff.

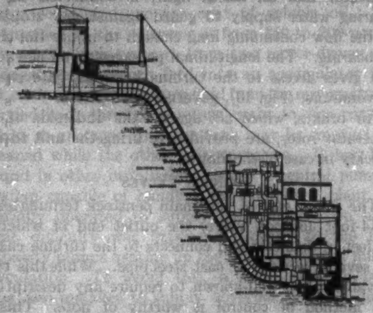

Fig. 10A—Cross-Section of Power House on Center Line of Main Unit

The steel columns are spaced longitudinally 26 and 24 feet alternately starting at the south end. The strength of the generator room steel was primarily determined by the necessity of providing cranes to handle the generator rotors which weigh about 300 tons each. The structural steel was so designed that it could be erected and the crane operated before the concrete walls were poured.

To guard against flooding due to the river level rising, the walls are designed to resist water pressure up to elevation 300, which is 16 feet above the base of the generators. No openings which might admit water from the river were permitted below this elevation, although temporarily a railway track is brought in at the south end at elevation 284, and is protected by stop logs.

The illustrations show the general design of the building. Some features which may be mentioned are: the arrangement of the generator cooling air intake ducts, which are carried up in the east wall between the columns to above elevation 300, where openings are provided to admit air either from outdoors, or from the interior of the generator room, an arrangement which takes up no floor space; the location of the generator room main floor at the top of the generator frame, a construction which provides space at small cost for the exhaust air ducts, fans, generator field equipment adjacent to the unit, and still allows a clear space around the generator on the main floor; the large steel sash windows in the generator room which are 21 feet in width by a total height of 38 ft. 4 in.; longitudinal tunnels in the substructure for handling turbine runners, and for piping; a longitudinal room, centrally located, for all conduit runs for control and instrument cable, with a corridor immediately above it the full length of the building; the location of control room over generator room at the center of the completed plant; provision of separate rooms for each 12-kv. oil circuit breaker; and particularly the symmetrical location of all main equipment for each unit—governors, transformers, oil circuit breakers, reactors, fans—in the 50-foot longitudinal space in which the turbine and its generator are situated.

The floor at the top of the generator frame materially reduces the unsupported height of the main crane columns, and does not affect the elevation of the crane rails, as the height of the crane is determined by the height of generator frame and shaft.

Access to the building from the main roadway and the electric railway on the top of the cliff is provided by the elevator in the administration end of the screen house, and a tunnel from the bottom of the elevator shaft to the power house floor on elevation 346 at the south end (Fig. 11).

In general, all plant services are provided in the southerly 75 feet of the station. In this area are located the sump pumps and motors, the air compressor, the service generators, transformers and switchboards, erection space, main station elevator, maintenance shops and stores, lubricating and insulating oil plants, battery rooms, a fully equipped hospital room, also kitchen and dining room and offices. The intention is to duplicate nearly all these services in the extreme north end of the ultimate stations.

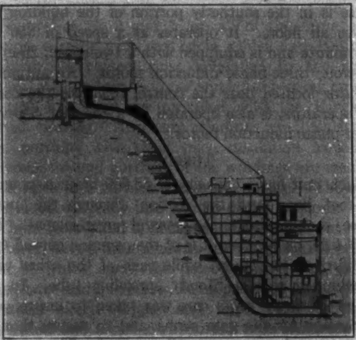

Fig. 11—Cross-Section of Power House Near South End

Permanent railway connections are provided by a track built along the river at the bottom of the cliff from the generating station to the Michigan Central Railway at the village of Queenston. A railway track is carried across the river side of the station building on an extended portion of the substructure to give access to the area to the south.

A 300-ton crane consisting of two separate units each having a capacity of 150 tons is provided in the generator room for handling generators, transformers and other apparatus. When the crane is to be used in lifting the generator rotor, which is the heaviest piece, an equalizer beam is used. This crane is supplied with a-c. motors and control.

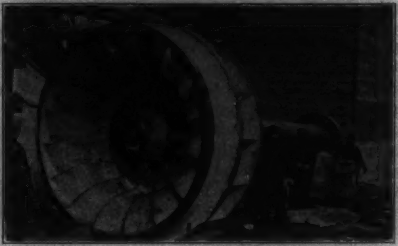

FIG. 12—TURBINE RUNNER

Electric hoists are located throughout the station to facilitate the handling of equipment.

The entrance elevator, from screen house to entrance tunnel, operates at a speed of 450 feet per minute, and is equipped with a 25-cycle, 550-volt, three-phase, variable-speed motor of the commutator type with brush shifting gear. The main elevator in the power house is in the southerly portion of the building and serves all floors. It operates at a speed of 350 feet per minute and is equipped with a two-speed, 25-cycle, 550-volt, three-phase induction motor. An automatic elevator located near the control room for the use of the operators, is also operated by a 25-cycle, 550-volt, three-phase induction motor.

TURBINES

Each unit has a capacity of 55,000 brake h. p. under 305-foot head and the section through the power house shows clearly the general arrangement. The draft tube on No. 1 unit is of the common curved type modified at the elbow, while each of the other units is equipped with a Moody spreading tube. In the design of these units care was taken to insure good lubrication for the gate stems and to assure that all wearing surfaces were well greased. The use of labyrinth seals on the runner rims (Fig. 12) cuts down leakage to a minimum. It will be noted on the section that the top portions of the draft tubes are of cast iron and these are so arranged that they can be lowered to facilitate the removal of the runner from below, thus dispensing with the necessity of dismantling of the generator. Owing to the presence of a considerable amount of sand in the water during periods of flood, and by reason of dredging operations in the upper canal, a pressure sand filtering plant has been installed to filter all water supplied to the lignum-vitae bearings to prevent scoring of the turbine shaft. The lignum-vitae bearings themselves are about six feet in length and in order to ensure lubrication over their entire length the water is admitted both at the middle and top of the bearing. A flow meter, with an indicator and an alarm light, is connected to the bearing water supply to guard against any stoppage of the flow continuing long enough to injure the shaft or bearing. The longitudinal passageway on elevation 264 gives access to the turbine bearings, gate stems, servomotors, (Fig. 13), governors and filters.

Air brakes, which act against the underside of the generator rotor, are provided to bring the unit to rest quickly in case of shutdown.

JOHNSON VALVES

The lower end of the main penstock terminates in a 14-foot Johnson valve, the outlet end of which is 10 feet in diameter and connects to the turbine casing by several sections of cast steel pipe. While this type of valve is too well-known to require any description, the method of control is worthy of note. This is accomplished through three 8-inch Johnson valves, which are in turn operated by pistons in cylinders under penstock pressure controlled by a three-way plug valve. When opening the valve to fill the scroll case, it is necessary to build up the pressure in the latter, in order to balance the pressure on the two sides of the plunger. The operation of the valve is so arranged that this is carried out automatically by a series of oscillations of the plunger, as soon as the control handle has been thrown into the opening position. In closing, the motion of the plunger is retarded near the end of the stroke to prevent an excess rise in pressure, due to too sudden closing, and also to protect the plunger seat against shock. The control is so arranged that the valve will close automatically in case of a break in the scroll case, and it is also provided with a remote hand control so that it may be closed, if necessary, from the control pedestal on the main operating floor.

FIG. 13—VIEW OF TURBINE DECK

Access to the valve is from the floor on elevation 264, the valve being located in a chamber which provides space for dismantling the valve.

The five-foot service penstock terminates in a steel plate *Y*. The two legs are each equipped with a 36-inch Johnson valve for each service turbine.

GOVERNORS

The governor system for the main units uses filtered water containing one per cent of soluble oil. This is supplied to the governor at from 150 to 200-pounds per square inch pressure from two motor-driven centrifugal pumps which feed into an accumulator tank for each unit. The return fluid from the servomotors is carried back through a return main to two concrete tanks so arranged that one tank may be emptied and cleaned while the other is in operation. It had been found in other installations, where a central pumping system capable of handling the completed plant was initially operated to supply only one or two units, that difficulty was experienced owing to the large capacity pumps heating up the small amount of fluid in circulation. To avoid this, a small capacity pump was also installed to supply governor pressure during the early stages of operation, and to be held afterwards in reserve for an emergency. To guard against a shutdown due to the failure of the governor pumps, an emergency connection has been provided to pass direct penstock pressure into the governor system header. This permits the governors to operate on penstock pressure, at any time that the pumping system is out of service, and has already been called into service since the first two units were placed in operation.

FIG. 14—No. 2 GENERATOR SHOWING CONTROL PEDESTAL AND GOVERNOR HEAD

Owing to the very small ratio of length of penstock to head (about 1¼ : 1) and the large flywheel effect of the generator rotors, the regulation of these units is a comparatively simple problem.

GENERATORS

The present five units are each rated at 45,000 kv-a., 80 per cent power factor, 12,000 volts, three-phase, 25 cycles at 187.5 rev. per min. They are capable of being operated continuously at 49,500 kv-a., with either voltage or current 10 per cent in excess of the rated values. The type is vertical (Fig. 14) with direct-connected shunt-field commutating-pole, 250-volt, 150-kw. exciter. The over-all efficiency of the generating units is slightly in excess of 97 per cent at 80 per cent power factor. The thrust bearing is designed to support a load of one million pounds, which is slightly in excess of the weight of the rotor plus the hydraulic thrust imposed by the turbine. Upper and lower guide bearings are provided the latter on account of the length of shaft and to keep the generator a self-contained unit.

The quantity of air required for cooling is 120,000 cu. ft. per minute. It is interesting to note that the weight of air passing through the generator every 2½ hours equals the total weight of the generator, namely 1,400,000 pounds. The units are completely enclosed, the air being drawn either from the outside of the generator room, or from both, and discharged through ducts into the atmosphere or to the different sections of the building for heating purposes. With five units in operation at rated load, there will be available for heating the building 5400 kw., which corresponds to 1.2 kw. per 1000 cubic feet of building contents. This amount of heat should be ample for heating the building at all times.

The maximum observable temperature which any portion of the unit will attain under rated conditions as obtained by thermocouples will not be in excess of 105 deg. cent. with 40 deg. cent ambient air. The temperature as obtained by thermocouples is indicated on the control pedestal adjacent to the generator, and also in the control room.

Units Nos. 1, 2 and 3 are all of the same make, having a rotor with cast steel spider and laminated built-up sheet steel rim, dovetailed to the spider. These three units have upper and lower bearing brackets of cast iron, and are provided with the Kingsbury thrust bearing. Armature windings are insulated in slot portions with sheet mica insulation ironed on, whereas the end portions of the windings are insulated with mica and varnished cambric taping. The stator is divided vertically into four 90-degree sections.

Units Nos. 4 and 5, being made by a different manufacturer, have a rotor made up of seven cast steel sections, five of which carry the pole pieces, the other two, one above and one below, being provided for additional flywheel effect. Upper and lower brackets are of cast steel and a spring supported type of thrust bearing is used. The armature coils are insulated throughout with mica tape. The stator is divided into three 120-degree sections.

The flywheel effect of each unit is 21,500,000 $W R^2$. The rotors are required to stand an overspeed of 185 per cent of rated speed. Insulation tests of 30,000 volts on armature and of 2500 volts on field and exciter are specified.

The over-all diameter of these units is 25 feet, the diameter of rotor over pole faces being 18 feet approximately. The shafts are 30 inches in diameter in the guide bearings and are provided with flange at lower end for bolting to corresponding flange on turbine shaft. The shafts are hollow with 8-inch diameter bore and are 30 feet 3 inches in total length. The over-all height of generators above the generator floor (elevation 284) is 26 feet 10 inches, thus above the main floor (elevation 297) only the top of the frame and the upper bracket, thrust bearing housing and exciter are visible (Fig. 15).

The weight of the complete generator is 1,400,000 pounds, that of the rotor 615,000 pounds. The largest piece to be handled by the cranes weighs 600,000 pounds.

Fig. 15—Interior View of Generator Room Looking North

EXCITATION

The principal source of excitation for each unit is the direct-connected exciter mounted above the generator. Each exciter has sufficient capacity to furnish excitation for one 45,000-kv-a. generator, and is rated at 150 kw., 250 volts. It is of the shunt-wound type with commutating poles and is especially designed for service with a generator voltage regulator.

The auxiliary source of excitation consists of a motor-generator set made up of a 250-volt 150-kw. shunt-wound d-c. generator, with commutating poles designed to carry the excitation of any one of the generators, and to work with the voltage regulator belonging to that unit. At present there is one auxiliary exciter set for five units, but in the completed station it is contemplated that there will be additional sets, each acting as a spare exciter for a group of machines. Each spare exciter may be connected to its own bus, to which the field of any generating unit of its group may be connected as shown in the diagram (Fig. 16). The auxiliary motor-generator sets are driven from the 2200-volt station service system.

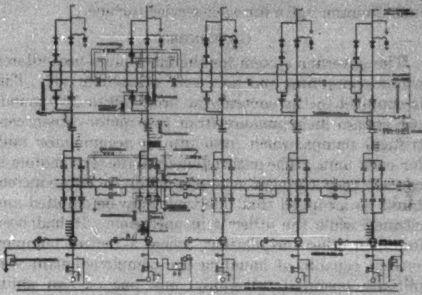

Fig. 16

Fig. 17—45,000-Kv-a. Single-Phase Transformer

A voltage regulator of the vibrating relay type controls the voltage of each generator. This regulator is equipped with compensation to prevent cross currents when units are in parallel on the 12-kv. bus, also with adjustable compensation for ohmic and inductive drop in transformer banks and lines. Each is provided with a device for maintaining a low maximum of exciter voltage in case of a drop of voltage due to short circuit, also with a device for cutting resistance into the exciter field circuit to limit the voltage in case of overvoltage due to overspeed or other causes.

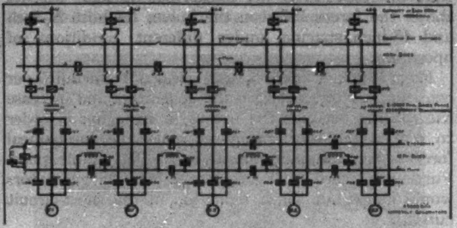

FIG. 18—QUEENSTON GENERATING STATION—WIRING DIAGRAM OF MAIN CONNECTIONS

No main generator field rheostats are used.

TRANSFORMERS

These are of the shell type and are individually rated at 15,000 kv-a., 25 cycles, 12,000/63,500/76,200 volts at 80 per cent power factor. There will be five banks of three, connected $\Delta - Y$ to give 110 to 132 kv. at rated load. The guaranteed efficiency at 80 per cent power factor is 98.25 per cent. The quantity of oil required for each transformer with its expansion tank is approximately 6500 Imperial gallons, the weight of the complete transformer is 100 tons. The over-all height is 28½ feet, and diameter of the tank is 9½ feet (Fig. 17).

Maximum observable temperature rise is specified at 50 deg. cent. with an observable temperature rise of 55 deg. cent. under a 10 per cent overload, above ingoing cooling water temperature of 25 deg. cent.

Insulation tests are 280 kv. and 33 kv. on high and low-voltage windings respectively.

The main tanks are of boiler plate with plate bottoms and covers. The tanks are required to withstand an internal pressure of 150 pounds per square inch and also a vacuum equivalent to 24 inches of mercury. The main tanks will be completely filled with oil, the expansions of the oil being provided for in separate tanks, but provision is made in the height of the main tanks so that operation without the expansion tanks will be safe.

The transformers are mounted on roller bearing structural steel trucks set on rails on elevation 297 to the rear of the 12-kv. switching equipment. A track runway throughout the length of the building connects to a cross runway at the south end, which permits moving the transformers to a position under the generator room cranes.

MAIN CONNECTION DIAGRAM AND SHORT-CIRCUIT STUDIES

The main wiring diagram (Fig. 18) shows the electrical arrangement of the main apparatus. A generator, bank of transformers and a line is considered a unit, each with a normal capacity of 45,000 kv-a. It will be impracticable to dispose of the power in blocks of this capacity and grouping of units will be essential. For this purpose 12-kv. and 110-kv. busses are provided. The diagram shows a double 12-kv. bus, only one of which, however, that with reactors, is being installed, but space is being provided for the second or emergency bus, and this may be installed later if conditions warrant.

Extremely interesting studies were carried out to determine the mechanical, magnetic and thermal effects on conductors under normal and abnormal operation with different groupings.

In the analysis practically all possible conditions of operation were considered. A key diagram was prepared with symbols representing groupings of units.

Referring to Figs. 19 and 20, I, II, III or IV indicates that 1, 2, 4 or 8 generators are paralleled on the low-voltage bus. If followed by *R* as II *R*, etc. the generators are paralleled through a reactor. If followed by *S* as II *S*, etc. the generators are connected to a synchronizing bus through a reactor. *a*, *b*, *c* or *d* indicates that 1, 2, 4 or 8 generators are paralleled on the high-

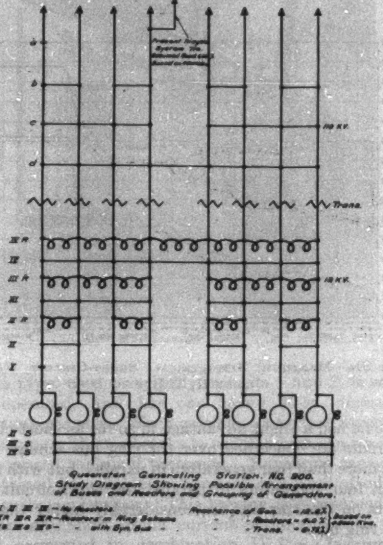
a
b
c
d
110 K.V.
Trans.
IV R
IV
III R
12 K.V.
III
II R
II
I
II S
III S
IV S
Queenston Generating Station. NC. 900.
Study Diagram Showing Possible Arrangement of Busses and Reactors and Grouping of Generators.
I II III IV — No Reactors
II R III R IV R — Reactors in Ring Scheme
II S III S IV S — " with Syn. Bus "
Reactance of Gen.
" Reactors
" Trans.
Based on

FIG. 19—DIAGRAM FOR SHORT-CIRCUIT STUDIES

voltage bus, so the significance of III *R d* may be readily understood as two groups of four generators each connected through reactors on the low-voltage side and the eight units paralleled on the high-voltage bus.

The short-circuit values are given as the r. m. s. values of the first symmetrical wave of current times the normal voltage times square root of three.

From the studies it was found that the star bus scheme had a slight advantage in so far as short-circuit currents are concerned over the ring bus scheme with not more than four generators in parallel, but with more than four generators in parallel the short-circuit currents on the star bus are considerably higher than on the ring bus.

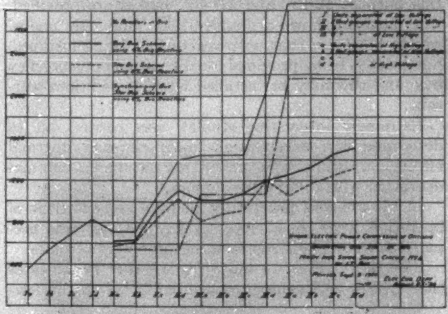

FIG. 20

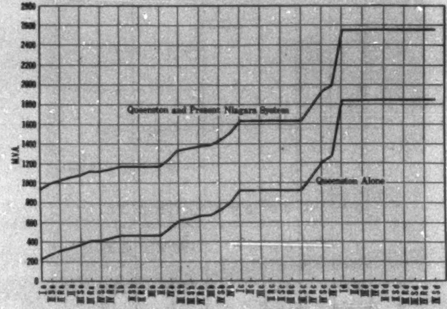

FIG. 20A—MAXIMUM SYMMETRICAL SHORT-CIRCUIT VALUES ON H. T. BUS

With eight generators operating in parallel on the 12 kv. bus the r. m. s. value of the first wave of the symmetrical short-circuit current may reach a value of 140,000 amperes with no reactors between generators. Using 4 per cent reactance (based on the capacity of a generator, namely 45,000 kv-a.) in bus reactors between the generators in the ring bus scheme 73,000 amperes would obtain and 104,000 amperes in the star bus if that scheme were used.

For the above short-circuit values (140,000, 73,000 and 104,000 amperes) the forces between the busses, spaced two feet apart, would be 5120 lb., 1420 lb. and 2870 lb. respectively per linear foot of bus. Fig. 21 shows the forces between the busses for both 24-inch and 45-inch spacing under different conditions of operation.

From these studies it was decided to install 5 per cent bus reactors between the generators and increase the spacing between the busses to 48 inches in order to reduce the short-circuit currents and mechanical forces to a minimum within the limits of available space. Further increase in the reactance between generators would cause but slight reduction in the short-circuit currents.

These curves were used as a basis in deciding upon the strength of bus supports to use and the rupturing capacity of the oil circuit breakers required. The oil circuit breakers which are used are suitable for operation under conditions at least as severe as IV *R c*.

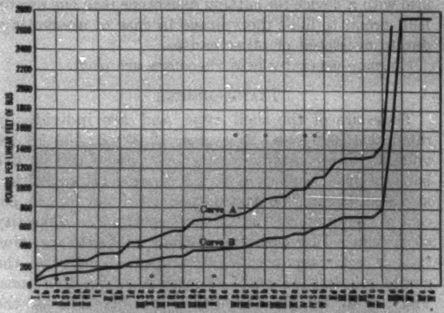

FIG. 21—MAXIMUM STRESSES ON L. T. BUSSES

CONTROL ROOM

The electrical control of the station is centered in the control room which is situated at elevation 361 above the generator room over units 4 to 6. A room approximately nine feet high underneath the whole control room permits control conduits to be brought in from the longitudinal conduit room and distributed to the various switchboards in an accessible and convenient manner. In the control room, the switch controls, indicators and dummy busbars are mounted on bench board sections, arranged in the general form of the arc of a circle. To the rear of the bench board are vertical panels carrying the necessary indicating instruments. Further back are the panels carrying the recording meters and relays, placed face to face. The completed switchboard will consist of bench board and panels for 9 or 10 units.

At each end of the main board is a five-panel board for controlling the main connections of the station service. This consists of bench board, instrument panels, recording meter and relay panels. Beneath each bench board and immediately behind each panel is a slot through the floor into the room below to permit easy installation and tracing of circuits.

Fig. 22—12-Kv. 3000-Ampere Oil Circuit Breakers Installed in Their Compartments

Control Pedestal

On the main floor, near the governor of each unit (see Fig. 14) is a "control pedestal." This carries necessary hydraulic and electrical meters to enable the attendant to keep in touch with operating conditions affecting the complete generating unit. It also carries a telephone and signal indicators, connected to the control room, and a pull button switch by which the generator oil circuit breakers and field breakers may be tripped in case of emergency.

Signal System

For each unit, a dial-type signal system is installed between the control bench board and the control pedestal near the generator, by which instructions can be transmitted from the operator in charge to the generator attendant. This is supplemented by special telephone connections at each pedestal.

Oil Circuit Breakers

Oil circuit breakers for 12-kv. service (Fig. 22) are rated at 15-kv., 3000-ampere continuous capacity. These are of two types, but the structural steel supports and general dimensions are such that they may be readily interchanged.

Fig. 23—135-Kv. 600-Ampere Oil Circuit Breaker

One type, used principally in units 1 and 2, is solenoid-operated, and has one heavy 36-in. diameter steel tank per pole. Each pole has contacts of inverted brush type with two breaks in series, which can readily be increased to four if necessary. Rupturing capacity is obtained by using large amount and head of oil in a very strong retainer. This breaker is guaranteed to rupture any short-circuit current obtainable with the plant connected in combination IV *R c*. Insulation will withstand 80 kv. for one minute.

The second type, used principally in units 3, 4 and 5, is motor-operated with two grounded tanks per pole. The arc is broken in oil in a very strong explosion chamber surrounding each arcing contact, arranged with baffles to shoot a stream of cool oil under pressure across the path of the arc. The main contacts of the wedge and finger type are in air. This breaker is guaranteed to rupture any short-circuit currents obtainable under combination IV *R d.* Insulation will withstand a 55-kv. test for one minute.

Oil circuit breakers for 110-kv. service are rated at 135-kv., 600-ampere continuous capacity. They are of the solenoid-operated type with one tank per pole of heavy construction. In each pole there are four breaks in series, each break having a special quick break feature to increase the rupturing capacity. Each breaker is guaranteed to rupture any short-circuit current obtainable with combination IV *R c.*, and will withstand a test of 280 kv. for one minute. Bushings will withstand 350 kv. for one minute.

Fig. 24—12-Kv. Bus Insulator

The control circuit voltage for operation of all breakers is 250 volts d-c. All breakers have ventilated tanks.

The 12-kv. circuit breakers are installed in individual rooms on two floors between the generator room and the transformers, with the main busses occupying an intermediate floor. These rooms are ventilated to the generator air discharge shaft. The leads from the breakers are carried through the wall at the rear through porcelain bushings, this giving a minimum of connecting material in these rooms.

The 110-kv. breakers (Fig. 23) are located on one floor at elevation 346, the breaker on the direct circuit from transformer bank to transmission line being separated entirely from all other breakers by walls. The breakers for each unit group connecting to the busses are in one room which has walls around all floor openings to prevent spread of oil.

Every switch room is drained into the general drainage system, and the doors to the rooms are provided with master-keyed locks. A designation symbol for every breaker is in use by which each breaker and its position in the connection may be readily identified.

12-Kv. Bus and Connections

The results of the short-circuit current study showed that a strong construction would be required for the 12-kv. bus and connections from the generator terminals to the transformer terminals. The combination of the 3000-ampere normal current capacity adopted, with the mechanical strength required, made this bus structure a unique problem. From consideration of this, it was decided that no cable would be used on any of these 12-kv. connections.

The spacing of the phases finally adopted was 48 inches for the main bus, breaker and transformer connections and 37 inches for the generator leads to the bus. These spacings with a calculated short-circuit current having an assymmetrical peak of 170,000 amperes give maximum forces of 485 lb. per foot for 48-inch and 630 lb. per foot for 37-inch spacing.

It was decided that a single-unit bus support to resist a force of 10,000 lb. applied at the bus clamp should be obtained. This would allow a spacing of supports along the bus of about 5 ft. giving a factor of safety of 3 on the support under maximum load conditions. A single-unit porcelain bus support of smooth surface, with cast iron hardware cemented on, and having an ultimate strength of 10,000 lb. in cantilever (applied at the center of the bus) and an 80,000-volt, 25-cycle, flash-over, was finally obtained (Fig. 24).

Fig. 25—Disconnecting Switches, 3000-Ampere, 12,000-Volt, with Operating Mechanism

The smooth porcelain was adopted with the intention of obtaining every advantage possible in the strength of the porcelain unit and making the cleaning of the units easier.

The bus copper adopted was three bars, 4 inches by ¼ inch, laid flat on the insulator cap. It was decided to mount the bus supports directly on the floors and walls and by the wide spacing of phases dispense with the usual barriers. This arrangement puts the copper into the plane of force in the position of its greatest strength. Tests in the laboratory showed that there is a real danger in using such a spacing of bus supports along the bus that the stresses set up by 25-cycle currents will coincide with the natural period of vibration of the length of copper, thus producing a case of mechanical resonance. On account of the low strength of copper, it is not possible to space the bus supports at the maximum distance considering the short-circuit forces above. The sagging of the copper due to its own weight is a limiting factor in the arrangement adopted.

Fig. 26—Disconnecting Switch, 13-Kv., 600-Ampere

Disconnecting switches of 3000-ampere capacity (Fig. 25) are provided on each side of every oil circuit breaker and are located in separate rooms behind the breakers. They are arranged to be operated in sets of three by a hand-operated mechanism with hand wheel outside of the room in which the disconnecting switches are mounted. These mechanisms are locked in the open or closed position by individual Yale locks with master keys for the station. The blades of the switches are locked in the closed position by the operating mechanism.

Pilot lamps mounted beside the hand-operating mechanism indicate the position of the switches and whether the oil circuit breakers are open or closed. This system was chosen in preference to the added complication of a mechanical or electrical interlock between the circuit breakers and the disconnecting switches.

Motor-operated disconnecting switches were considered but it was decided that the advantages would not warrant the extra expense.

Wherever the copper bars are taken through floors and walls, bushings are installed. They consist of a central porcelain tube mounted in a panel of ebony asbestos. The flash-over value is 80,000 volts at 25 cycles. This design gives a very effective and inexpensive bushing.

It is proposed to have all copper bars covered with flame-proof insulation.

110-Kv. Bus and Connections

A continuous current-carrying capacity of 600 amperes was adopted for all high-voltage circuits, which required the use of one-inch diameter, iron pipe size, copper tubing for all 110-kv. connections. As provision is made for ultimately increasing the potential to 135 kv., a standard 42-inch high, corrugated single-piece porcelain post with cemented-on cast iron hardware was installed. These units have a cantilever and torsion strength of 40,000 inch-lb. and have a dry flash-over value at 25 cycles of 350 kv.

600-ampere, 135-kv. disconnecting switches (Fig. 26) of double break, center rotating post, operated by hand mechanism in gangs of three, were adopted, using the same porcelain post as the bus support. These posts, complete with hardware, are interchangeable with the bus supports.

Relay Protection

The simplicity of the main connections in the plant and especially the absence of 12-kv. feeders makes it possible to use differential relay schemes for protection of apparatus and connections. This allows rapid automatic removal of defective equipment from service with a minimum of disturbance to operation. The apparatus and main connections of each unit are divided into the following groups:

Generator,
Main 12-kv. bus,
Auxiliary 12-kv. bus (when installed),
12-kv. connections of transformer,
Transformer bank,
110-kv. connections of transformer,
110-kv. busses.

Each conductor where it leaves the group carries a current transformer These current transformers are so connected to relays that if the current in each phase leaving the group is not equal to the current entering that phase, the relay will carry the difference in the currents, or in other words the current to a fault. If there is no defect inside the groups, current leaving will be equal to current entering and there will be no relay action, no matter how heavy the through current. To insure correctness of operation, the following precautions have been taken:

1. Current transformers are of special design to give correct ratio even with heavy currents.

2. Impedance in secondary wiring has been kept low by short connections. The only equipment connected is the relays which are in the differential circuit and carry fault current only.

8. Current transformers are placed outside the oil

circuit breakers which would isolate any group so that a defective breaker would be cleared on both sides.

All differential relays are of the instantaneous overload plunger type except for transformer differential which are inverse time overload induction type. Generator differential relays have also a hand reset feature to increase the certainty of operation.

Each differential group of relays is arranged with multiple contact relays to trip the necessary circuit breakers to isolate the defective equipment. In case of the generator differential, the field circuit breakers are also tripped.

In addition to the differential relay groups the following relays have been installed (Fig. 16):

1. A relay in the ground connection of each unit to give an alarm in case of ground current. No switches are tripped.
2. A directional relay on each generator, of the three-element induction wattmeter type restrained by a spring. The principal function of this is to check careless synchronizing. It trips out the generator oil breakers.
3 A ground relay on the 12-kv. connections close to the transformer bank on each unit. It protects this section of the wiring including the transformers 12-kv. bushings which are not included in any of the differential groups. This is an inverse time overload induction type relay.
4. A set of inverse time overload relays of the induction type on each outgoing line. This consists of one relay for each phase and one for grounds.
5. A set of inverse time overload relays in the main 12-kv. bus between units to separate them in case the units drop out of step with each other.

An annunciator is provided with each unit which indicates by a drop and an alarm bell which relay was operated.

Several operations of portions of the relay equipments have shown that they function as intended.

All current transformers on the main circuits are of the bushing type, those for 12-kv. circuits having the core and secondary winding mounted on high-grade condenser bushings placed over the three 4-inch by ¼-inch copper bars. This particular design permits several secondary windings to be mounted on the same bushing.

The 12-kv. potential transformers are of strong construction with an especially high insulation test and are connected through protecting resistors, fuses, and disconnecting switches to the main circuits, the disconnecting switches being in a separate room from the fuses.

REACTORS

Reactors are installed only between 12-kv. main bus sections, *i. e.*, between generators. They are of the cast in concrete type with the conductors and the concrete impregnated with varnish. The continuous current-carrying capacity is 2380 amperes with a temperature rise not exceeding 80 deg. cent. above 40 deg. cent. ambient temperature. They will safely carry short-circuit current for 12 seconds. The rating is 12,000 volts, 25 cycles, single-phase 5 per cent reactance based on 2165 amperes, the normal rated current of one 45,000-kv-a. generator. Protective resistors are mounted within the reactor and connected to its terminals.

These reactors are located on the generator floor on elevation 284, below the 12 kv. oil circuit breaker rooms.

SERVICE APPARATUS

All services except oil switch control and signal lamps are 25-cycle operated. Power is obtained from two turbine-driven three-phase service generators each rated at 2200 kv-a., 2300 volts, 25 cycles, 500 rev. per min. In addition, power for service is available from a 12-kv. line from the Ontario Power Company.

These service turbines are rated at 2800 h. p. each at 500 rev. per min. under 305 feet head. On these units, the governors, governor pumps, etc., are entirely independent of the main governor system. Oil is used as a medium in these governors, and is supplied by two gear pumps with motors mounted on the same base as the pressure tank.

In general, all motors of 25 h. p. or larger are operated at 2200 volts, whereas smaller three-phase motors are 550 volts.

Generator air exhaust fans, pumps, compressors, shop equipment are electrically operated.

Direct current for operating oil circuit breakers, rheostats and other small motor-driven devices is at 230 volts and is obtained from a 15-kw. motor-generator set. The induction motors are supplied from a 550-volt service feeder. The generator floats on a 230-cell, 154-ampere hour lead storage battery. The generator and battery equipment is in duplicate, so that one generator and battery unit can float on the load at approximately constant voltage while the other battery is being charged. A middle tap is brought from each battery for connection to emergency lighting circuits.

Switchboard indicating and signal lights are supplied from 32-volt d-c. circuits to enable tungsten lamps to be used. Power is obtained from a 4.5-kw., 32-volt generator driven by a d-c. motor from the 230-volt battery, and floating on a 16-cell, 23-ampere-hour lead battery. This unit is in duplicate with one motor-generator and one battery for each 230-volt battery. Better economy is expected from these lamps than from the standard higher-voltage ones.

Arrangement of Service Apparatus. The service electrical circuits are shown in Fig. 27. The principal distributing center called "Section A" is located near the service generators. The two service generators, the incoming feeder from the Ontario Power Company which has been stepped down through a 1500-kv-a., three-phase, 12,000 to 2300-volt transformer, and all service feeders are connected to a main 2300-volt bus through cell-mounted oil circuit breakers. The generator, incoming feeder and main bus breakers are electrically operated from the main control room. The service feeder breakers are hand-operated. A 2300-volt transfer bus is provided for emergency operation. Power for 550-volt services is obtained from the 2300-volt system through three 300-kv-a. 2300 to 550-volt transformers to a main and a transfer 550-volt bus. All 550-volt oil circuit breakers are hand-operated and mounted on pipe framework. Section "B" center is located near unit No. 4. It is supplied by two feeders from the 2300-volt bus in Section A. These will eventually be continued to Section C station at the north end of the completed plant, which will be similar to Section A. Section B contains transformers for local services and is a switching center for 2300-volt feeders. The fans and governor pump feeders are arranged as "ring" feeders between Sections A and B so that each has two sources of power. The auxiliary exciter sets are on a ring feeder from Section A to Section C. The generator bearing oil pumps and the governor pressure air compressor have each 550-volt feeders from Sections A and B. The service generators are protected by differential relays and by inverse overload induction-type relays, the latter type being used also for protection of the feeders.

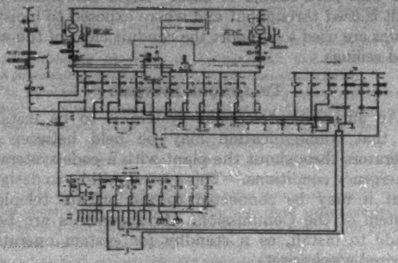

FIG. 27—DIAGRAM OF SERVICE CIRCUITS

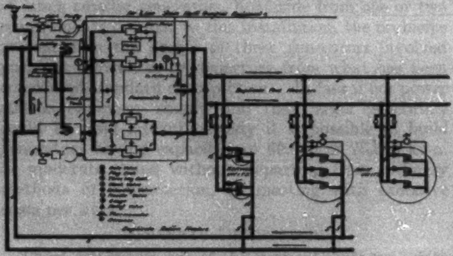

FIG. 28—DIAGRAM OF LUBRICATING OIL SYSTEM

The lubricating oil piping diagram for the main and service generators is shown in Fig. 28. This consists of a central plant of purifying and pumping apparatus with pressure and return headers all in duplicate. Each half of the system is of sufficient capacity for five units. Oil is distributed to the generators by pump pressure and the return oil passes into a settling tank. Any water or sediment settles to the bottom of the tank and passes out to a centrifugal purifier and the purified oil is returned to the system. Each generator requires about ten Imperial gallons per minute of oil. In addition to the duplicate oil pumping equipment, the system is provided with a storage of oil under air pressure suitable for operating the plant for one hour.

The transformer oil system is shown diagrammatically in Fig. 29. Tanks of sufficient capacity to hold all the oil from one bank of transformers are provided and are connected to a "good oil" and a "bad oil" header, which in turn connects with the five banks of transformers. The valves for the storage and purifying equipment are symmetrically arranged and located so that all operations may be performed from one point. The valve arrangement allows the pump and filter press or purifier to be connected with any tank and either header, meanwhile the operator can see at a glance just what connection he is making.

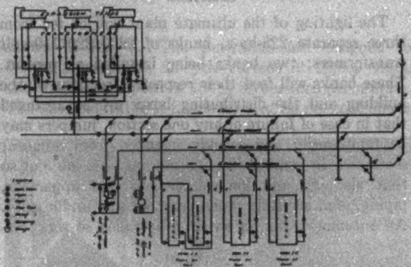

FIG. 29—DIAGRAM OF TRANSFORMER OIL HANDLING SYSTEM

The switch oil apparatus follows the same layout as the transformer oil system, though on a smaller scale. There is no piping connection between the transformer and switch oil systems.

Water for cooling purposes for the transformers and for the generator bearings is obtained from a header connected through valves to the main penstocks, thus eliminating pumping equipment. This header, located in west piping tunnel at elevation 267, is sectionalized by valves between penstocks. Duplicate feeders to each generator and bank of transformers are installed. The house service supply and fire hydrant supply are also obtained from the main header, which also furnishes water through the filters to the turbine bearings.

110-Kv. Outgoing Circuits

The 110-kv. circuit on each unit is brought out of the building through pent houses on the roof by means of compound-filled porcelain bushings. Oxide-film lightning arresters are installed indoors on elevation 375 on each unit.

The single-circuit transmission line for each unit is of 45,000-kv-a. capacity, using steel-cored aluminum cable. The connections of 605,000-cir. mil. cable from bushings to the transmission line are carried on suspension-type insulators, from the tower structure on the roof to special towers on the edge of the roadway at the top of the cliff in front of the screen house, thence to a tower structure on the roof of the screen house, from which the circuits spread out to the standard transmission terminal towers. Two circuits connect to existing transmission lines at Niagara Falls, and additional new circuits under construction extend westwards to connect to more distant existing stations on the 110-kv. system.

Lighting

The lighting of the ultimate plant will be fed from three separate 225-kv-a. banks of 2200/220/110-volt transformers; two banks being installed at present. These banks will feed their respective sections of the building and the distributing boxes are so arranged that in case of failure of any one section, jumpers may be temporarily and quickly installed from adjacent sections. In general, the lighting has been laid out so that all high and low-voltage bus and apparatus, piping, etc., are fully illuminated without undue glare. An automatic transfer switch is installed so that certain circuits may be connected to the 230-volt control battery in case of failure of the a-c. supply.

All feeders from the switchboards are composed of single-conductor rubber-covered double-braided cables. Small wiring from panel boards is of standard rubber-covered double-braided conductor except that in places where excessive moisture is encountered 30 per cent para rubber is used. Rigid galvanized conduit is used throughout and where exposed to moisture shims are used to support the conduit clear of the walls and ceilings.

Telephone Systems

An automatic telephone system is to be installed so that communication may be held between the operators throughout the plant with a code system for emergency conditions. This system will be so designed that it may be connected to the private telephone system of the Commission. Arrangements are being made to install, as a standby for system operation, a wired wireless set.

The engineering and construction work on this development have been carried out under the direction of the commission's staff with Mr. H. G. Acres as chief hydraulic engineer, and Mr. E. T. J. Brandon as chief electrical engineer.

The author wishes to put on record his appreciation of the loyalty and devotion of the entire engineering and construction staffs of the Commission in carrying through the work on this development.

Discussion

For discussion of this paper see p. 507.

Description of the 45,000-kv-a. Queenston Generators

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Review of the Subject.—*Notwithstanding the very large rated capacity of the 45,000-kv-a. generators for the Queenston power house of the Hydro-Electric Power Commission of Ontario, their essential construction features are not different from those of much smaller rated generators. The generators are of the vertical shaft type with two guide bearings, and a thrust bearing. The thrust bearing is located above the stator and carries the weight of the complete rotating elements of the generator and water turbine. Each generator is provided with a direct-connected exciter.*

The flywheel effect required for satisfactory speed regulation of the turbines necessitated the use of auxiliary flywheels mounted on the shaft adjacent to the generator rotor. The rotor is constructed with a number of cast steel wheels which together form the rotor spider for carrying the pole pieces. The pole pieces are made of punchings and are attached to the rotor with three dovetails per pole. The coils are made of copper strip wound on edge.

The stator frame is split vertically into three sections to conform with foundry and shipping limitations but the core is built up without being split. The stator windings consist of form-wound, diamond-shaped coils, each slot containing two coil sides. The coils are made of stranded conductor and are insulated with mica tape, which affords more or less flexible insulation. The ends of the coils are braced against the distorting effect of severe short circuits in such a manner as to permit expansion and contraction of the copper without injury to the mica insulation. The armature phase connections are made with bus rings supported from the stator frame, making all connections accessible.

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THE purpose of this paper is to describe briefly a few of the construction features of the 45,000-kv-a. generators manufactured by the Canadian General Electric Company for the Queenston power house of the Hydro-Electric Power Commission of Ontario. Because of the fact that the rated capacity of these generators is greater than that of any generators ever before constructed, there is a tendency to create an impression that their construction would involve radical changes from the more or less familiar types of much smaller generators, but aside from one or two requirements peculiar to this installation, the problems presented in the design of these generators involved no great difficulties or departure from what has been considered standard construction. In fact if our power station engineers should find that larger generators could be used advantageously it is possible to build generators having capacities of 60,000 or 75,000 kv-a. at moderate speed without departing from ordinary methods of construction, or meeting with excessive costs per kv-a.

General Description

These generators are of the vertical shaft type with revolving fields and stationary armatures. They have two guide bearings and a thrust bearing. A substantial base ring supports the stator frame and carries the spider bracket for the lower guide bearing. The thrust bearing is supported by a deck or spider spanning the top of the stator frame and carries the rotating parts of the generator and turbine. There is a direct-connected exciter mounted at the top of the generator. A general view of the complete unit is shown in Fig. 1. The generators are designed to deliver three-phase, 25-cycle current at 12,000 volts, and rotate at a speed of 187½ revolutions per minute. The full-load rating is 45,000 kv-a. at 80 per cent power factor, with a temperature rise not exceeding 65 deg. cent. as observed by detectors imbedded in the slots of the stator core or by resistance measurements of the

Fig. 1—General View of the Assembled Unit

Presented at the A. I. E. E. Annual Convention, Niagara Falls, Ontario, June 26-30, 1922.

stator or rotor windings. The full-load efficiency including all mechanical and electrical losses is guaranteed to be not less than 97¾ per cent at 100 per cent power factor. The exciters are rated 150 kw. at 250 volts.

STATOR FRAME, CORE AND WINDINGS

The stator frame is divided into three sections vertically, in order to keep the weight within the foundry capacity and provide sections of a size and weight that could be easily handled in the shop and in transportation. These castings are probably the largest in size and weight ever used for generator construction, the frame being 24½ ft. in diameter by 10 ft high, and weighing, complete, approximately 90 tons. In building the core of such a large generator it is desirable to avoid joints that divide the core into sections because looseness and vibration of the laminations are liable to develop due to the unequal expansion of the frame and core, and the difficulty in arranging clamps capable of exerting sufficient pressure. Therefore it was decided to build up the core in the power station thus obtaining a continuous ring. The slots in the stator core are unusually large for a waterwheel type generator, being as large as those commonly used in the large high-voltage turbo-generators. The stator winding is of the common "Barrel" type with two coil sides per slot. Each turn of the coils is insulated with mica tape applied by hand after the coil has been formed. The coil insulation consists of mica tape put on by hand with a special compound sticker between layers. This process results in a uniform insulation on the full length of the coil and when slightly heated a sufficient flexibility is obtained to permit the removal and assembly of coils without great danger of damage to the insulation. The semi-plastic condition of the insulation also permits the expansion and contraction of the copper, due to changes in temperature, with a minimum disintegrating effect on the mica in the insulation.

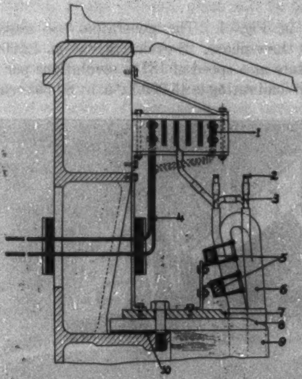

FIG. 2—ARRANGEMENT OF STATOR COIL CONNECTIONS AND COIL BRACING RINGS

1. Phase bus rings.
2. Pole connections.
3. Group connections.
4. Terminal leads.
5. Bracing rings.
6. Stator coil.
7. Clamping flange of core.
8. Clamping fingers.
9. Punchings or core.
10. Removable shims to allow taking up settling of core.

FIG. 3—THE ROTOR

STATOR COIL SUPPORTS

The projecting ends of the coils at both the top and bottom are braced against one another by small wooden spacers, placed between the sides of the coils, and the whole winding is supported at each end, against the distorting effect of short circuits by two complete steel rings which are supported from the frame by suitable iron brackets. The windings are bound securely to the supporting rings with treated cord. This method of binding permits of a certain amount of flexibility that is desirable to allow for the expansion and contraction of the coils due to changes in temperature. The bracing rings are covered with insulating material not only for insulating purposes but to act as a cushion for the coils to rest against, and to take the sharp blows resulting from severe short circuits without cutting the coil insulation.

POTENTIAL WAVE

The stator coils are chorded to take advantage of fractional pitch properties in obtaining a voltage wave form as near as possible to the ideal sine wave, and to eliminate the objectionable harmonies.

ARMATURE CONDUCTOR

The section of copper necessary to carry the current in the stator windings being too large to use a single strand, the conductor was subdivided into a number of strands of small section to facilitate the forming of the conductor in the coils and also to reduce largely the eddy current losses in the copper. The phase connections of the stator winding have been taken care of in a rather unusual manner by the use of a bus ring arrangement supported from the inside of the stator frame. The connections between these bus rings and the windings are made with flexible connections which can be disconnected. This arrangement allows free access to all the connections for cleaning and inspection, and permits the removal of damaged coils without disturbing the connections.

VENTILATION

Air for cooling the generator is admitted to the pit beneath it, through ducts from outside the station, or from the generator room, and is drawn into the machine by the blower action of the rotor. The air is expelled through the openings in the stator frame into a chamber surrounding the generator, and is then exhausted by a fan through a ventilating shaft through the roof, or to the different parts of the power house as desired. Because of the large volume of air required (about 120,000 cu. ft. per minute) it was necessary to give special consideration to the ventilation in the construction of the generator and power house. The unique provisions in the design of the power house for the generator ventilation are described in another paper being presented at this meeting.

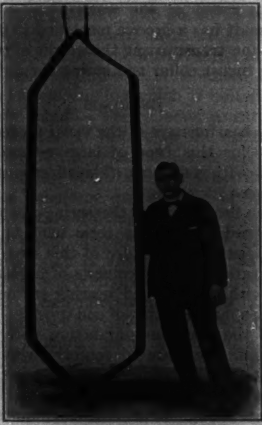

FIG. 4—STATOR COIL

FLYWHEEL EFFECT

To meet the requirements of the hydraulic equipment in regard to speed regulation under conditions

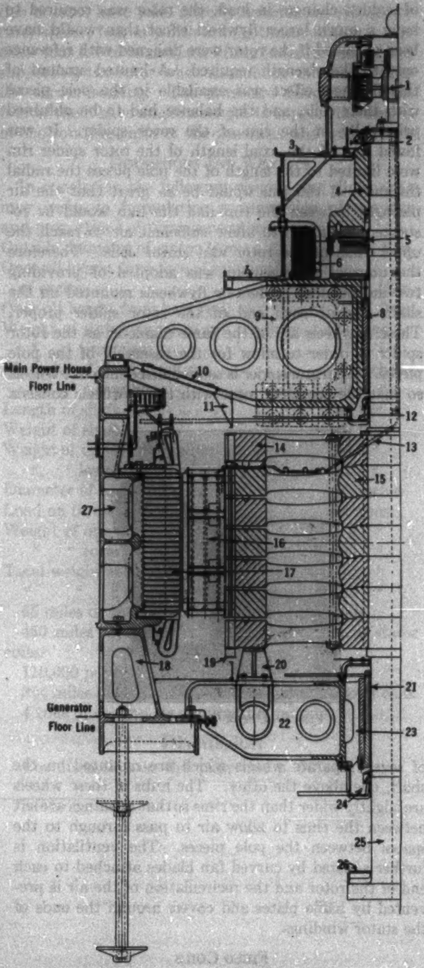

FIG. 5—COMPLETE ASSEMBLY SECTION OF UNIT

1. Exciter.
2. Collector rings.
3. Exciter platform.
4. Thrust collar.
5. Spring thrust bearing.
6. Water cooling coils.
7. Thrust bearing platform.
8. Upper guide bearing.
9. Upper bearing bracket.
10. Cover plate and manhole.
11. Air baffle ring.
12. Upper oil drip pan.
13. Collector leads.
14. Flywheel section.
15. Rotor spider section.
16. Pole piece.
17. Stator core.
18. Base ring.
19. Fans.
20. Pedestal for supporting rotor.
21. Lower guide bearing.
22. Lower bearing bracket.
23. Lower guide bearing housing.
24. Lower oil drip pan.
25. Shaft.
26. Coupling bolt guard.
27. Stator frame.

of sudden changes in load, the rotor was required to have a much larger flywheel effect than would have been obtained if the rotor were designed with reference only to the strength required. A limited amount of this flywheel effect was available in the pole pieces with their coils, and the balance had to be obtained principally in the rim of the rotor spider. It was found that if the axial length of the rotor spider rim were limited to the length of the pole pieces the radial thickness of the rim would be so great that the air passages between the rim and the hub would be restricted too much to allow sufficient air to reach the upper ends of the rotor and stator coils. Therefore the unusual arrangement was adopted of providing two independent spiders or flywheels mounted on the shaft, one at each end of the rotor spider proper. These flywheels are of the same diameter as the rotor spider in order to allow for the assembly of the pole pieces. The rotor spider is sectionalized into five wheels so that the complete rotor with the flywheels consists of seven separate wheels which are mounted on the shaft, one above the other. The hubs of these wheels are slightly wider than the rims so that openings are left between the rims to allow air to pass through to the spaces between the pole pieces. The ventilation is further assisted by curved fan blades attached to each end of the rotor and the recirculation of the air is prevented by baffle plates and covers around the ends of the stator windings.

FIG. 6—UPPER GUIDE BEARING

FIELD COILS

The field coils are probably the largest ever made. Each coil is wound from a continuous strip of copper 1100 feet in length and weighing 2600 pounds. This strip is wound on edge in the usual manner and the adjacent turns are insulated from each other with asbestos and mica. The insulation between the coil and the pole core is of mica sheets while the insulating collars are of asbestos board so that the coils can be subjected to considerable heat without injury. This fire-proof insulation was not thought necessary because of an excessive temperature rise in normal service, but to prevent injury to the coils by a fire in the generator resulting from a failure in the stator winding.

POLES

The pole pieces are of the usual construction having ⅛-inch punchings riveted together between heavy cast steel end plates. Each pole has three parallel *T*-shaped dovetails which are designed to withstand the stresses due to double normal speed, without exceeding half the elastic limit of the material. Each pole with its coil weighs five tons and the peripheral velocity of the pole face at normal speed is over two miles per minute. The flywheel effect of the complete rotor is equivalent to 21,000,000 pounds at one foot radius. The shaft which is 30 inches in diameter in the bearings, has a solid forged coupling. In order to insure ample stiffness of the shaft, the critical speed with the rotor and shaft in a horizontal position was kept well above the run-way speed of the water-wheel. The upper end of the shaft has a groove machined in it to receive a split ring for transmitting the weight of the rotating parts to the thrust collar and spring thrust bearing.

BEARINGS

The guide bearings are of the usual General Electric construction for this type of large generator. They are provided with a number of small grooves for lubricating purposes.

The thrust bearing is of the spring supported type and is designed to carry a total load of 500 tons. Briefly, the distinctive feature of this type of bearing is that the stationary part consists of a relatively thin steel plate with a babbitted bearing surface which is supported by a large number of coil springs. The slight flexibility of the plate in conjunction with the spring support permits the plate to conform with any slight irregularity either in the supporting structure or the shaft and thrust collar without causing local unit pressures large enough to prevent the maintenance of a film of oil between the bearing surfaces. The thrust bearing operates in a bath of oil which is renewed at a comparatively low rate with clean oil from the station oil system. The heat generated in the bearing is taken up directly by the oil as it passes through and around the bearing plates and is then removed from the oil by water cooling coils immersed in the oil bath.

BEARING BRACKETS

The upper bearing bracket or bridge-tree for supporting the thrust bearing and exciter, has eight arms and is of cast steel. Because of shipping limitations it is split into halves which are joined together with fitted bolts. The complete bracket was tested at the factory with a load of 1000 tons by means of hydraulic jacks. This test load is double the normal operating load and gave assurance that the castings were sound. Cast steel was used for these brackets not only because of its greater strength but also to limit the deflection to a value that would not interfere with the adjustment of the bearings or other parts of the generator and turbine. The calculated deflection of 47 mils was reasonably consistent with the observed value of 35 mils. The castings were slightly thicker than the drawing dimensions which fact probably accounts for the difference between the two values.

The openings between the arms are closed with sheet steel covers. Manholes of generous dimensions in these covers permit ready access to the upper part of the rotor and stator for cleaning and inspection.

In view of the fact that this power development is public enterprise and therefore will be open to public inspection, much attention has been paid to the design of the thrust bearing bracket, exciter and platforms, and railing, to obtain graceful proportions, and at the same time present an impression of strength and massiveness in keeping with the great power capacity of the generator and station. Two platforms are provided the lower one for inspection of the thrust bearing and the upper one for the inspection of the exciter and collector rings. The exciter armature is mounted on a short shaft with a forged coupling which is bolted to the top of the generator shaft. The collector rings are mounted on the generator shaft just below the exciter coupling and in case the exciter armature is removed for repairs it is not necessary to disturb the generator collector rings and the generator can be kept in service while the exciter armature is being repaired.

The lower guide bearing bracket is supported on the inner projection of the base ring. The opening for the guide bearing is large enough to pass the coupling on the shaft. The guide bearing shell is made as light as is consistent with good construction to facilitate removal, and is supported in the bearing bracket by the housing. Both the shell and housing are assembled and removed from below the bracket. The arms of this bracket have pads directly beneath the rim of the rotor spider, four of which are for the air brakes. The other four are to be used for lifting jacks for raising and supporting the rotor when assembling and dismantling the thrust bearing. The arms are designed so that four of them have ample strength to support the weight of the rotating parts of the generator and waterwheel.

DIMENSIONS AND WEIGHTS

In conclusion the following weights and dimensions may assist in formulating a conception of the size and proportions of these generators:

Outside diameter of stator frame	24 ft. 6 in.
Over-all height from face of coupling to top of exciter	33 ft. 10 in.
Over-all height from base ring	28 ft. 3 in.
Weight of stator with core and windings	175 tons
“ “ base ring	37 “
Diameter of shaft in rotor	32 inches
“ “ coupling	53 “
Length of shaft	30 feet
Weight of shaft	40 tons
Weight of upper bearing bracket	50 “
“ “ lower “ “	12 “
Diameter of thrust bearing	69 inches
Load on thrust bearing	500 tons
Weight of one pole piece with coil	5 “
“ “ rotor spider (7 sections)	190 “
Total weight of rotor	310 “
“ “ “ generator with exciter	625 “

65 miles of wire used in one set of stator coils.

450 miles of tape used to insulate one set of stator coils.

110,000 punchings required for stator core.

3½ miles of copper strip used for one set of pole coils.

4 tons of cooling air required per minute.

Discussion

For discussion on this paper see p. 507.

Design of 45,000-Kv-a. Generators, Queenston Plant

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Fellow, A. I. E. E. — Canadian Westinghouse Company

The water power development at Queenston, Ontario, which made use of the combined head of Niagara Falls and the Niagara River Rapids below the Falls, involved the design and construction of, what up to the present time are the largest hydroelectric generators built. Owing to the size limits met in these generators certain interesting design problems were encountered. The more important of these problems dealt with the design of (1) the armature winding, (2) the upper bearing bracket and (3) the rotating spider. The solution of these problems is briefly discussed and a tabulation of major dimensions and weights of the generators is given.

THE initial installation at the Queenston Development of the Hydro-Electric Power Commission of Ontario consists of two vertical shaft type alternating-current generators, each rated at 45,000 kv-a., 12,000 volts, 80 per cent power factor, three-phase, 25 cycles, 187½ rev. per min. nominal, or 49,500 kv-a., 13,200 volts maximum. A third duplicate unit will shortly follow the first two machines.

These units, as far as the records show, are the largest hydroelectric generators yet built and put into service. On account of their size, both in kilovolt-ampere rating and in physical proportions some interesting design problems were raised. These problems were divided into two classes, (1) electrical, and (2) mechanical, with perhaps the latter predominating.

Fig. 1 gives a sectional view of the generator unit. Fig. 2 gives a sectional view of the generator turbine and surrounding structure and indicates the flow of the cooling air through the generator and ducts. Each unit consists of the following component parts:

Stationary armature with base ring.

Upper bearing bracket, which supports the upper guide bearing and the thrust bearing.

Kingsbury thrust bearing.

Revolving field.

Shaft, with one-half coupling forged on the lower end for connection to the turbine shaft.

Lower bearing bracket, which carries the lower guide bearing, brakes and lifting jacks.

Direct-connected exciter.

DESIGN OF ARMATURE WINDING

The design of the armature winding involved, in addition to the ordinary questions of heating, efficiency, etc., the solutions of four important special problems, namely, (a) to obtain a distribution of the armature coils such as to produce a resultant voltage wave practically free from interference with adjacent telephone lines, (b) to obtain sufficient cross-section of copper in the armature coils to carry successfully the rated current, and at the same time not have the conductors of such proportions as to result in excessive eddy current loss; (c) to insulate the coils with materials that could meet the requirements for high dielectric tests and a high maximum temperature limit, even though the operating temperatures are low; and (d) so to support the end windings as to enable them to resist the enormous stresses that would be set up under short-circuit conditions.

The solutions worked out for these design problems were as follows:

(a) It is a well understood condition in the design of electrical generators that starting with the usual field flux form, the actual resultant wave will more nearly follow the desired law, other factors being the same, provided that the conductors, producing the resultant wave, are distributed at a maximum number of different positions about the armature periphery; *i. e.,* in a maximum number of slots. It was not found possible in these units to use an actual number of slots sufficiently large to insure the desired results. However the same effect was obtained by employing

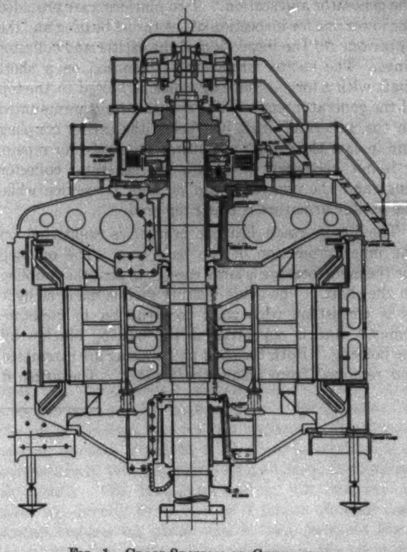

FIG. 1—CROSS SECTION OF GENERATOR

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instead of the usual whole number of slots per pole a fractional number of slots per pole. The design selected had 19½ slots per pole which gave a distribution of the winding equivalent to 39 slots per pole. Fig. 3 indicates the distribution of the slots in two successive poles. One pole is shown directly above the other to indicate the relative phase position of the slots.

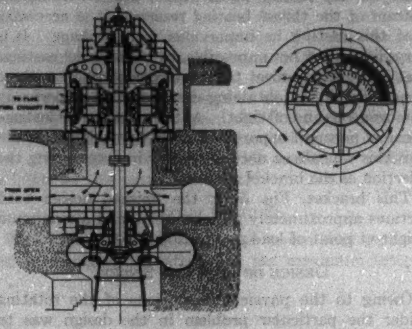

Fig. 2—Showing Flow of Cooling Air

Since the slots per phase in successive poles, in series, are displaced one-half slot pitch with reference to each other, it is apparent that the effect is equivalent to double the actual number of slots per pole.

(b) To minimize the eddy current loss it is necessary (1) to keep the over-all dimensions of the conductors (groups of wires in parallel) small, and (2) to reduce the dimensions, at right angles to the direction of the fluxes, of the individual wires that form the conductors, to relatively small values. To accomplish these results the total copper cross-section per phase was divided into four parallel circuits and the conductor in each of these circuits was subdivided as shown in the slot cross-section, Fig. 4. Each slot contains two coil sides consisting of two conductors each, *i. e.*, four conductors per slot, made up of nine wires in parallel per conductor. Each conductor is divided, depthwise of the slot, into seven layers, in consideration of the effect of the flux of self-induction. The two layers nearest the air gap were again subdivided into two parts in the width of the slot. The coil was also sunk in the core an additional distance over that ordinarily required for the slot wedge. The latter two features were to minimize the effect of the air gap flux that fringes into the slot.

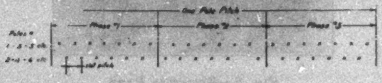

Fig. 3—Armature Winding Distribution
× Represents a slot

Each of the wires marked "*A*" in Fig. 4 was insulated throughout its entire length with mica tape to insure positive and permanent separation between the various strands.

Since all the wires are continuous throughout the length of the coil the subdivision, of course, repeats itself in each conductor.

(c) Each group of wires forming a single conductor was insulated with mica tape. The conductors were assembled with mica strips between them to form the coil. The straight section of the coil which is embedded in the armature slot was brushed with bakelite, and then pressed in a hot press to solidify and consolidate the wires. The result of this treatment is a rigid coil in which the wires cannot be disturbed by subsequent insulating and assembling operations.

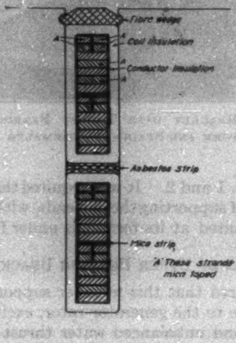

Fig. 4—Section of Armature Slot

The straight coil sides were insulated with a micarta-folium wrapper which consists of mica pasted to a very thin paper to give it the necessary mechanical support during the insulation process. The wrapper was first loosely applied to the coil by hand and then ironed into the finished product by electrically heated irons that revolve around the coil softening the bond and exerting a uniform pressure, thus slipping and tightening the wrapper until the insulation takes on the character of a compact wall of mica. The ends of the coil projecting from the core were insulated with mica tape adjacent to the copper and with varnished cloth outside of the mica tape. Varnished cloth tape on the outside of the coil is preferable since it can be sealed to exclude dirt and oil much better than can mica tape. Insulation in the form of narrow tape was used on these parts in order that the ends be flexible.

This insulation was required to meet successfully a dielectric test to ground, and between phases, of thirty thousand volts for one minute. It was also required that it safely withstand a maximum total temperature of 150 deg. cent.

(d) The coil ends were bent away from the air gap at an angle of about 45 degrees to provide space below the boreline for the clamping blocks. The coil ends were braced against distortion under short-circuit conditions by clamping them with through bolts between parallel insulating blocks which are bolted to angle-shaped brackets attached to the frame. This construction is shown in the cross-section views of the generator, Figs. 1 and 2. It was required that this bracing be capable of supporting the coil ends, with the generator short-circuited at its terminals under full voltage.

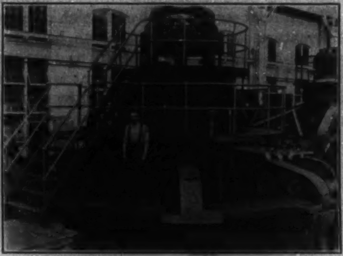

FIG. 5—UPPER BRACKET WITH THRUST BEARING, EXCITER, PLATFORM AND STAIRWAY ASSEMBLED

DESIGN OF UPPER BEARING BRACKET

It was required that this member support the combined loads due to the generator rotor, exciter, turbine runner, shaft and unbalanced water thrust amounting to approximately 1,000,000 pounds. Its design involved the consideration of three principal requirements, namely, (a) the fundamental requirement that it be capable of supporting the load within the safe limits of the material used; (b) that when fully loaded the deflection from the horizontal be less than the clearances between the turbine and generator rotating and stationary parts, and (c) that the character of the material and the design used be such that any vibrations set up by unbalanced conditions in the turbine would not be taken up by the bracket and transmitted to the generator stator.

Obviously these matters are so interwoven that they cannot be considered independently and, therefore, will not be taken up separately.

In designing this supporting member consideration was given to the use of three materials, structural steel, cast steel and cast iron. All factors considered, cast iron seemed the one best suited to the purpose. It was found in considering steel, either structural or cast, that while the requirements of ultimate strength could be readily met, its high degree of flexibility and resilience made it necessary to use sections greatly in excess of the requirement for strength in order to limit the deflection and the possibility of sympathetic vibrations. As the sections required with steel to meet the latter requirements approximated those needed in cast iron for strength, and as cast iron is not as flexible or resilient as steel, the iron was selected.

As the top surface of the upper bracket forms the bottom of the thrust bearing reservoir it is necessary that this casting be impervious to oil leakage. It is very difficult, if not impossible, to obtain steel castings that will entirely meet this requirement whereas there is no difficulty in obtaining cast iron that is perfectly homogeneous and oil tight. As the matter of oil leakage is one of no small importance in the operation of such a unit this was also a deciding factor in determining the selection of the bracket material.

This bracket, Fig. 5, in the finished design used sections approximately 2 inches thick and a maximum height at point of load application of 5½ feet.

DESIGN OF ROTATING SPIDER

Owing to the physical dimensions of the rotating spider the particular problem in the design was to select a construction in which the material throughout would be of uniform quality. On account of the well-known difficulties in making castings of such large sections and of obtaining uniformly homogeneous metal, it was impossible to make the spider of the ordinary "cast wheel" type. The "laminated rim" type of design, Fig. 6, was therefore adopted as the one best suited to meet the requirements.

FIG. 6—ROTATING PART

This design used an inner cast steel spider which consists of a hub and arms but has no rim. The rim is built up using over-lapping ⅛-in. rolled steel plates that are dovetailed to the spider arms in a manner similar to that used in attaching the armature punchings to the frame. In addition to being attached to the spider by the dovetails, the rim is clamped between heavy steel end plates by means of through bolts that pass through the entire laminated rim and the end plates. This design results in a rim structure of perfectly uniform material of known quality, to a degree impossible to obtain with castings. In this design the rim was not only self supporting as to radial stresses, entirely neglecting the dovetails, but was also capable of carrying the weight of the poles and field coils when operating at a maximum speed of 347 rev. per min.

The two large vent spaces provided in the central part of the spider were to provide additional cooling air inlets for this part of the unit.

OPERATING RESULTS

With the generators in regular commercial service and operating under rated load, the maximum temperature rise measured by embedded temperature detector is 55 deg. cent.

GENERAL DIMENSIONS AND WEIGHTS

The principal dimensions and weights of the generators are as follows:

Maximum over-all diameter	25 feet.
Height from floor line to top of frame	13 ft. 8 inches.
Maximum over-all height from floor line	26 ft. 10 inches
Diameter of shaft at coupling	2 ft. 6 inches
Total weight of copper	50,000 lb.
Weight of rotating part	615,000 lb.
Total weight of generator unit	1,400,000 lb.
Load on thrust bearing	1,000,000 lb.
Flywheel effect of rotor	21,500,000 lb-ft.^{2}

Discussion

For discussion on this paper see p. 507.

Features of Main Power House Transformers for Queenston Plant

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Review of the Subject.—*Interest in the main step-up transformers for the New Queenston generating station of the Hydro-Electric Power Commission of Ontario centers largely about their great physical size and the heavy short-circuit currents to be dealt with. Physically they are the largest single-phase transformers in operation today. In spite of the fact that they are for 25-cycle service, to our knowledge even their kv-a. rating is exceeded by only one bank of single-phase transformers now in operation, namely, the 70,000-kv-a., 60-cycle bank at the Colfax Station of the Duquesne Light Company.*

Figures are given for the weights and dimensions of these transformers and their component parts as well as the performance calculated from test results.

The mechanical forces in 25-cycle transformers are inherently high because of the relatively large number of turns necessary to develop the voltage, and because of their relatively low impedance to the flow of short-circuit currents. As the forces depend upon the square of the ampere-turns, it is evident that both the above conditions contribute materially toward increasing the forces.

To understand the bracing necessary to withstand the electromagnetic forces developed under short-circuit conditions, it is necessary to understand the nature of these forces as well as their magnitude.

The nature and magnitude of the mechanical forces existing between current carrying coils are discussed, (1) for a single turn coil in space, (2) for two single turn coils arranged concentrically and lying in the same plane, (3) for two single turn coils arranged coaxially and lying in parallel planes.

The conclusion is reached that as long as primary and secondary coils are adjacent there is no limit on the shape of the coil from the mechanical point of view, as all stresses acting in the plane of the coils are neutralized and there is therefore no force of any magnitude tending to distort the coils. The conclusions reached when single turns are considered hold equally as well for coils or groups of coils, so that in considering the forces in a transformer these fundamentals must always be kept in mind.

Thus by interleaving the primary and secondary coils, it is possible to overcome completely any limitations which the mechanical forces with other arrangements of coils may dictate and to choose a coil shape which adapts itself most readily to the solution of the other important problems of the design, namely, insulation and ventilation.

The Queenston transformers employ the interleaved type of construction familiarly known as the shell form, with rectangular pancake coils forming the alternating groups of primary and secondary coils.

The distribution of the mechanical forces in these transformers is analyzed in detail. The effects of imperfect distribution of turns and of taps are shown to be very undesirable. All of the required voltages could have been obtained with considerably fewer leads and taps but the reduction in the insulation difficulty through the elimination of extra leads would have been accompanied by an increase in the mechanical forces due to unbalancing conditions on tap connections. In these transformers the maximum stress occurs on the first under voltage tap and has a value equal to 136 per cent of the maximum stress with the full winding.

Having analyzed the various types of forces to be met with in the design of transformers of this type of construction, it will be interesting to examine the mechanical supports which have been provided in these units.

The proper ventilation and insulation of a transformer is equally as important as the adequate mechanical support of the winding. The system of bracing used in these transformers is particularly interesting, in that, in spite of the substantial construction used, the other vital factors of ventilation and insulation have not been impaired in the least.

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INTRODUCTION

IN the years 1909 and 1910 there were designed, built, and installed at the Niagara Falls substation of the Hydro-Electric Power Commission of Ontario, the first nine 3000-kv-a. water-cooled transformers, to raise the three-phase power from 12,000 volts to a nominal transmission line potential of 110,000 volts. The data available at that time for designing, building and operating 110,000-volt apparatus were rather meager.

Six years later, in 1916, there were installed in this same substation the first three 7500-kv-a. transformers having the same characteristics. Six years of experience with the original units on the Hydro-Electric Power Commission's system with many data from other sources, made the problem of designing and building the 7500-kv-a. units relatively a much simpler one.

Interest in the main step-up transformers for the new Queenston generating station of the Hydro-Electric Power Commission of Ontario centers largely about their great physical size and the heavy short-circuit currents to be dealt with. Physically they are the largest single-phase transformers in operation today. In spite of the fact that they are for 25-cycle service, to our knowledge, even their kv-a. rating is exceeded by only one bank of single-phase transformers now in operation, namely, the 70,000-kv-a., 60-cycle bank at the Colfax station of the Duquesne Light Company.

The design of transformers of such great capacity requires the solution of many difficult mechanical problems. This phase of the design is particularly difficult when the transformers must be made self-protecting against the short-circuit stresses incident to a 25-cycle system of the magnitude contemplated for this development. Planned for an ultimate capacity of some

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fifteen 45,000-kv-a. generators, the Queenston station will be among the largest ever projected.

Physical Dimensions and Weights

A few statistics as to the physical size of these units might be of interest. They have a nominal rating of 15,000-kv-a. output at 80 per cent power factor delivered at 63,500 volts with 12,000 volts impressed. To compensate for the drop through the transformers under the above load condition, the open-circuit voltage is 67,200 volts. They have a maximum rating of 16,500 kv-a. under the same conditions of loading as given above with a guarantee of 55 deg. cent. rise in temperature as measured by change in resistance.

Fig. 1

They are operated in banks of three, delta-connected on the low-voltage side, star-connected on the high-voltage side, to step up the generated power from a nominal voltage of 12,000 volts to transmission line potential. Taps are provided on the high-voltage windings so that the line potential may be varied between 110,000 to 132,000 volts.

The windings contain over 11,000 pounds of copper and the magnetic core contains over 60,000 pounds of punchings. The bare transformer weighs 99,000 pounds. The case, cover, base and various accessories weigh 46,500 pounds. Complete, with oil, the unit weighs 205,500 pounds.

Owing to the large dimensions and the great weights of the parts, especially cores and tanks (see Figs. 1 and 18), methods of handling at the manufacturer's plant and at the site of the power house as well as transportation facilities had to be considered in laying out the design.

The case is a cylindrical boiler plate shell, 9 ft. 6 in. outside diameter, and stands 21 feet from the rail to the flange at the top. The height from the rail to the top of the high-voltage terminal is slightly over 28 feet. The great height of the transformer is partly on account of the crowned cover and bottom which were necessary to meet the requirement of 150 lb. per sq. in. pressure, or 24 inches of vacuum, test on the tank. The bare tank with cover weighs 28,000 pounds. The tanks were delivered complete on the power house site.

The heaviest pieces are the transformer cores (Fig. 18). Ready for shipment they measure 7 ft. 2 in. by 7 ft. 4 in. floor space by 12 ft. 4 in. from floor line to top of insulating washers. Each core was shipped complete as shown in Fig. 18, except that the terminal supports were removed. The windings and insulation having been thoroughly dried and treated, the cores were sealed in oil in a special shipping tank. The shipping tank, oil and core weighed 142,000 pounds. At the manufacturer's plant and at Queenston the cores were handled with special lifting rigs by overhead cranes.

At Queenston the transformer cores were transferred directly to the main tanks, and flooded with oil. This procedure obviated the necessity of any drying and treating of the windings or insulation after installation, furthermore it greatly reduced the time required to put the units into actual service.

Rating and Performance

The Hydro-Electric Power Commission of Ontario required these transformers to be rated to develop 63,500 volts when delivering 15,000 kv-a. at 80 per cent power factor, with 12,000 volts applied to the low-voltage terminals at 25 cycles, and further that they would operate successfully with as high as 13,200 volts applied without excessive no-load current and losses.

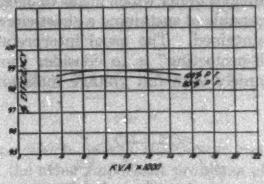

Fig. 2.—Efficiency Curves

With the above rating the transformers have a regulation of 5.85 per cent. This gives current rating of the windings as follows: 236 amperes for the high voltage, 1320 amperes for the low voltage. All tests to determine the performance of these units were made with above current values.

Complete tests to determine the no-load and full-load losses, also temperature runs with full-load current and voltage in the windings by the opposition method, have been made at works of the Canadian Westinghouse Company, Limited. All temperatures of windings were determined by the increase in resistance method. The results obtained from temperature runs indicate that with full kv-a. output under normal voltage and frequency with 45 imperial gallons (54 U. S.) of water per minute through the cooling coils, the temperature of the windings will not exceed 68.5 deg. cent. or a temperature rise of 43.5 deg. cent. above ingoing water at 25 deg. cent.

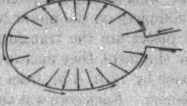

Fig. 3

Fig. 2 indicates the efficiency of these transformers at 100 per cent and 80 per cent power factor, calculated from the measured no-load iron losses and full-load wattmeter copper losses at 75 deg. cent.

IMPORTANCE OF MECHANICAL PROBLEM

The mechanical forces in 25-cycle transformers are inherently high because of the relatively large number of turns necessary to develop the voltage, and because of their relatively low impedance to the flow of short-circuit currents. As the forces depend upon the square of the ampere-turns, it is evident that both the above conditions contribute materially toward increasing the forces. Frequently the conditions under which a transformer operates are such that external impedance considerably reduces the magnitude of the short-circuit currents which can flow through the transformer. On small systems advantage can frequently be taken of this external impedance to make the transformer good for the conditions under which it has to operate without making it capable of sustaining a short circuit with full voltage maintained. The usual interpretation of the phrase "self-protecting" is to consider the worst case possible, namely with full voltage maintained.

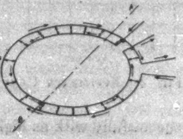

Fig. 4

On large systems only very slight advantage can be taken of external impedance owing to the great concentration of power. With systems of the capacity of the Niagara system, a further complication arises from the limitation in the amount of current which can safely be interrupted by the circuit breakers.

Frequently it will be found advisable so to group the machines and busses as to limit the amount of current which can flow into a fault to an amount which will be within the breaker capacity. This was the case in the layout of the Queenston station so that some slight advantage could be taken of the fact that generators and their respective transformers will never operate in parallel without reactors between the units. The greater the capacity of the individual transformer banks on a system in proportion to the total generating capacity, the greater becomes the difficulty of making them fully self-protecting and the less becomes the necessity for their being made so.

NATURE OF FORCES IN TRANSFORMER COILS

To understand the bracing necessary to withstand the electromagnetic forces developed under short-circuit conditions, it is necessary to understand the nature of these forces as well as their magnitude. Consider first a single circular turn of wire carrying current. If the leads enter the turn along a radius their effect may be neglected and the forces on this turn are due only to the reaction between the various elements of the turn upon one another; thus as illustrated in Fig. 3, the forces acting are all radially outward from the center of the coil and are equally distributed around the circumference of the coil.

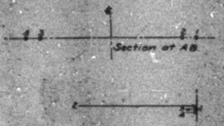

Fig. 5

That the effect of the leads may always be neglected becomes clear when it is remembered that, in the usual case, the coil will consist of a large number of turns instead of a single loop and the forces on portions of the coil will be many times those which can exist between the entering leads. Now consider two concentric circular turns lying in the same plane, and carrying equal currents. The forces are still radial as shown in Fig. 4, with two cases to be considered, first, currents in two turns in phase and second, currents in two turns out of phase. The forces illustrated in Fig. 4 are for the condition of the currents being out of phase by 180 deg. as would be the case between a primary and secondary winding. The forces between the two turns are repulsive and tend to keep them concentric. If the current were in phase in the two coils the forces would become attractive and any eccentricity would tend to increase the force at the point of least separation until the two turns are finally brought into contact.

To analyze this case more closely consider a section *A B* of the two turns shown in Fig. 4. Fig. 5 shows conditions at this point. For convenient reference, the different conductors have been numbered and the direction of flow of current is indicated in the conventional manner. There is a strong repulsion between conductors 1 and 2 due to their proximity and a repulsion of the same order of magnitude between conductors 3 and 4. These are not the only forces acting, however. Conductor 1 is attracted by conductor 3 and repelled by conductor 4. The magnitude of these forces compared with the magnitude of the forces between conductors 1 and 2 is inversely as the distances between them. Thus, when the diameter of the circles is great in comparison with their separation the forces on conductor 1 due to conductors 3 and 4 are in opposite directions and of very nearly the same magnitude. The excess of the attraction toward conductor 3 over the repulsion from conductor 4 slightly decreases the repulsion between conductors 1 and 2. By this process of reasoning it may be clearly demonstrated that the only forces which need be considered are those between adjacent coil sides.

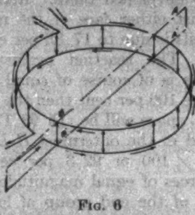

Fig. 6

The other common grouping of windings employed in transformer construction is the inter-leaved grouping in which all coils are coaxial and primary and secondary groups alternate with one another across the opening in the magnetic core. The mechanical forces between windings arranged in this manner are radically different from what they are with the concentric construction. Refer to Fig. 6, in which the turns are of the same diameter and lie in parallel planes. Fig. 7 shows a cross-section looking in the direction *A B* indicated in Fig. 6. The direction of the various forces acting is shown by the arrows. On any conductor there are three forces acting. For example on conductor 2 there are a strong force of repulsion from conductor 1, a very much weaker force of repulsion from conductor 3, and a force of attraction toward conductor 4 of the same order of magnitude as the repulsion from conductor 3. The horizontal component of the attraction 2-4 practically wipes out the repulsion 2-3, and its vertical component detracts only slightly from the repulsion 1-2. The net result is that the only force of magnitude is that between conductors 1 and 2 and all forces acting in the plane of the coils are practically neutralized.

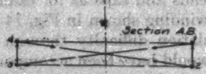

Fig. 7A

Fig. 7B

The conclusion is reached that as long as primary and secondary coils are adjacent there is no limit on the shape of the coil from the mechanical point of view, as all stresses acting in the plane of the coils are neutralized and there is therefore no force of any magnitude tending to distort the coils. The conclusions reached when single turns are considered hold equally as well for coils or groups of coils, so that in considering the forces in a transformer these fundamentals must always be kept in mind. Thus by interleaving the primary and secondary coils, it is possible to overcome completely any limitations which the mechanical forces with other arrangements of coils may dictate and to choose a coil shape which adapts itself most readily to the solution of the other important problems of the design namely, insulation and ventilation.

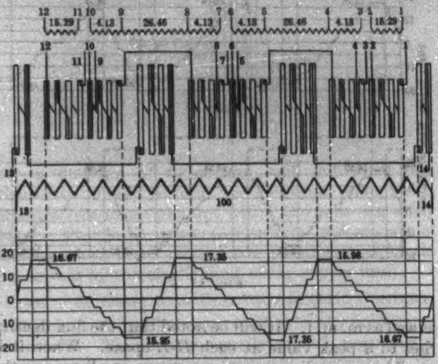

Fig. 8

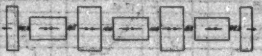

Fig. 9

Distribution of Forces in Queenston Transformers

The Queenston transformers employ the interleaved type of construction familiarly known as the shell form, with rectangular pancake coils forming the alternating groups of primary and secondary coils. The interlacing may be indicated symbolically *L H H L-L H H L-L H H L* there being three groups of high-voltage coils with which are associated a group of low-voltage coils on either side. This arrangement is called a 6-*H*-*L* grouping from the number of spaces high to low voltage which occur in the transformer. Fig. 8 shows a view of the top of the transformer, on which are indicated the connections and the development of winding. The figures adjacent to the development indicate the percentage of the total series turns in each section. Below the plan view has been plotted a graph of the magnetomotive force causing leakage across the opening between primary and secondary. The flux density will be proportional to the m. m. f. so that the same chart might represent induction just as well as m. m. f. It will be noted that the flux density rises to a peak value at each *H-L* space. When it is possible to equalize the ampere turns in all groups the value of all of these peaks will be identical and other conditions being the same, the magnitude of the repulsion at each *H-L* space will be the same. It is frequently impossible to get an exact balance and in such cases the magnitude of the repulsion at different *H-L* spaces will differ slightly. For example, refer to Fig. 10 and note the values of the ampere turns across various *H-L* spaces are + 16.67, − 15.98, + 17.35, − 17.35, + 15.98 and − 16.67 respectively. The total force against the end groups of coils is that due to the maximum value of ampere turns concentrated across any *H-L* space. This follows from the fact that each of the internal groups has a force acting against its opposite faces in opposite directions. Since the magnetic centers of all groups lie in the same plane, the resultant of two such forces is the algebraic difference. If there is an excess of one force above the other, it is transmitted to the next group and combines with the forces developed there. Referring to Fig. 9 the force against either face of the middle group of high-voltage coils is due to 17.35 per cent of the total ampere turns. The reaction against the adjacent low-voltage coils is of course of equal magnitude. If we call this force 100 per cent then the force developed in the next *H-L* space will be $(15.98/17.35)^2 \times 100$ or 85 per cent and in the outermost *H-L* spaces will be $(16.67/17.35)^2 \times 100$ or 92.3 per cent. Cancelling out opposite forces of equal magnitude it will be seen that the stress of the end group of low-voltage coils against the supports is due to the highest stress in any part of the windings.

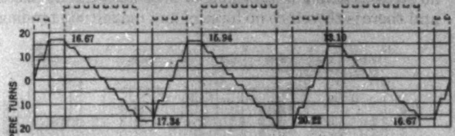

FIG. 10

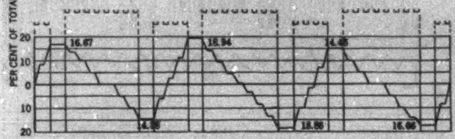

FIG. 11

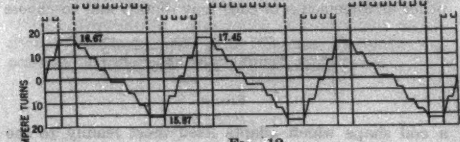

FIG. 12

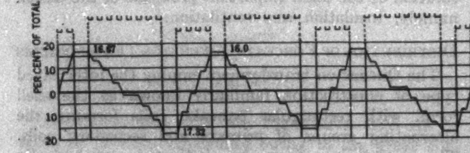

FIG. 13

100 per cent − 85 per cent = 15 per cent unbalanced force which adds to reaction of 85 per cent against right face of outer high-voltage group giving 100 per cent.

100 per cent − 92.3 per cent = 7.7 per cent unbalanced which adds to reaction of 92.3 per cent against right face of outer low-voltage group giving 100 per cent.

EFFECT OF TAPS

Taps always result in unbalanced magnetic conditions unless equal turns are cut out simultaneously from each group. This would lead to a very large number of taps and leads and in most cases the complication could not be justified. However, it should always be borne in mind that the greater the percentage of the winding tapped, the greater is the possibility of increasing the forces by unbalancing. Fig. 10 shows the magnetomotive force distribution on the first under voltage tap and Figs. 11, 12 and 13 under the other tap conections.

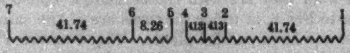

FIG. 14

All of the required voltages could have been obtained with considerably fewer leads and taps as for example with the development of winding shown in Fig. 14 but the reduction in the insulation difficulty through the elimination of extra leads would have been accompanied by an increase in the mechanical forces due to unbalancing conditions on tap connections. As will be noted from Figs. 8 and 11 to 13, the maximum stress in the Queenston transformers occurs on the first under voltage tap and has a value of $(20.22/17.35)^2 \times 100 =$ 136 per cent of the maximum with the full winding.

FORCE ON INDIVIDUAL CONDUCTORS OR COILS

Fig. 15 shows an enlarged section of one portion of Fig. 8. It will be noticed that the individual coils which make up this group do not lie in fields of equal intensity. In fact the field intensity increases almost uniformly from one edge of the group to the other, reaching a maximum value at the edge of the space *H* to *L*. To obtain the total force developed between any two groups the ampere turns in that group must be multiplied by the average flux density through the group. Since the field intensity increases uniformly the average will be one-half the maximum. It is almost self evident that the coils nearest the *H-L* space will develop the greatest repulsion owing to the intense field in which they lie. It is a simple matter to calculate the percentage of the total force developed in a given group, which is concentrated against the face of any particular coil. For example, the number of turns in the high-voltage coil nearest the low-voltage winding is 4.41/17.35 × 100 = 25.4 per cent of the total number of turns in that group. The average field intensity throughout this coil in per cent of the average field intensity for the whole group is

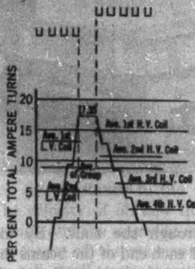

FIG. 15

$$\frac{17.35 - \frac{4.41}{2}}{8.62} \times 100 = 175.6 \text{ per cent.}$$

The percentage of the total stress developed against the first high-voltage coil will then be 0.254 × 1.756 × 100 = 44.6 per cent. Similarly the second high-voltage coil is subject to

$$\frac{4.41}{17.35} \times \frac{10.735}{8.62} \times 100 = 31.6 \text{ per cent, and the}$$

third high-voltage coil to

$$\frac{4.41}{17.35} \times \frac{6.325}{8.62} \times 100 = 18.6 \text{ per cent, and the}$$

fourth high-voltage coil to

$$\frac{4.13}{17.35} \times \frac{2.065}{8.62} \times 100 = 5.7 \text{ per cent, of the}$$

total force in that group.

In the same way it can be shown that the force against the first and second low-voltage coils is approximately 75 per cent and 25 per cent respectively of the total force developed in the group.

The spacing strips which separate the coils to form the ventilating ducts must give the coils ample support to withstand safely the highest value of stress that can be concentrated against it. The problem resolves itself into a question of supporting each individual turn frequently enough to limit the deflection under short-circuit stress to an amount which the coils can safely stand. This limit is set as much by the amount of bending which the insulation will stand without breaking, as it is by the elastic limit of the copper itself.

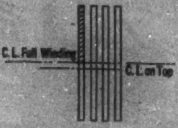

FIG. 16

EFFECT OF DISPLACED ELECTROMAGNETIC CENTERS

Tapping a coil will always result in locally unbalanced conditions. This applies equally as well, regardless of whether we are speaking from the electrical or the mechanical point of view. From the design point of view, taps are always very undesirable. The mechanical effect of taking a tap out of a group of coils is illustrated in Fig. 16, which shows the worst possible unbalancing due to a single tap in a group of four coils. With one-half of the turns in one coil idle, the shift in electromagnetic center lines would be 3.67 per cent of the width of the coil. Obviously the conditions would be worse with fewer coils in the group, the worst case being a single coil. The ideal arrangement would be where the electromagnetic center lines are maintained coincident under all possible combinations of connections. This ideal condition can be realized even when the design is handicapped by taps, provided the taps can be arranged to come at the connection between coils. Reference to Fig. 8 will show that on these transformers for the Queenston station, this problem has been successfully worked out so that the taps all come from connections between coils. In this way the possible displacement is limited to that obtainable with good manufacturing tolerances.

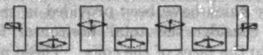

FIG. 17

When a displacement in center lines exists, the total force in the various planes parallel to the face of the coils may be resolved into components parallel and perpendicular to the plane of the coils. Fig. 17 shows a section through the upper ends of the coils of a transformer in which the displacement has been exaggerated to illustrate the nature of these stresses. With the displacement in the direction assumed the resultant forces are upward at the center of each low-voltage group and downward at the center of each high-voltage group of coils. Conditions are repeated at the lower ends of the coils so that the total vertical forces will be double those indicated in Fig. 17.

FIG. 18

METHOD OF BRACING EMPLOYED

Having analyzed the various types of forces to be met with in the design of transformers of this type of contruction, it will be interesting to examine the mechanical supports which have been provided in these units.

First to consider the total horizontal force perpendicular to the faces of the coils. Those portions of the coils which pass through the laminated core are securely held in place against these stresses by the punchings themselves. It is only necessary to supply supports for the portion which projects beyond the iron. Heavy steel plates are placed against the ends of the assembled groups of coils and insulation. By means of tie rods these plates are clamped about the ends of the coils to secure them against possible movement. Fig. 18 shows clearly the steel plates and the tie rods spanning them. Three rods are used on either side, two of the upper and one of the lower being visible in the picture. The others are concealed by the structural steel end frames but the holes provided to tighten these are clearly shown.

The weight of all the coils and insulation is carried on supports which are independent of the stacked up punchings which form the magnetic core. This support consists of two *T* beams with heavy spreader bolts between. One beam is inserted into each end of the opening through the coils. By means of the spreader bolts at each end of the beams they are forced apart until the opening in the coils is solidly blocked, and all the weight transferred to the lower supporting frame. Fig. 19 shows the lower *T* beam in position ready for the building of the coil, the photograph being taken on a unit of slightly different rating and characteristics. The *T* beams in the case of these transformers are made of phosphor-bronze in order to eliminate stray losses as they parallel a portion of the magnetic circuit. Fig. 18 also shows quite clearly this construction. These *T* beams also take care of any vertical

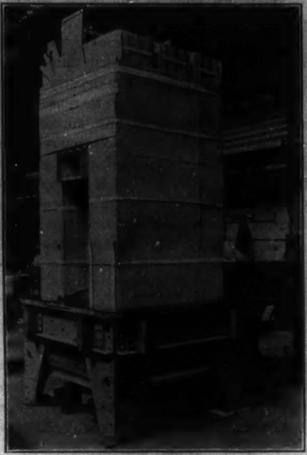

FIG. 19

FIG. 20

stresses due to possible discrepancies in the electromagnetic centers of the primary and secondary coils.

Individual coils are braced by the use of specially designed spacing strips. The vertical portions are supported by "wavy" spacing strips which support each turn at frequent intervals without blanketing any portion of the coil. The group of wavy strips in any duct is cleated together at several places and the cleats dovetail into the channels over the edge of the coils so that the strips cannot shift. The corners and the ends of the coil are braced by means of the ventilated spacers shown in Fig. 20. These spacers are formed of micarta in such a way that a solid piece of material is obtained having ribs at an angle to its length and open spaces between the ribs. The slant of the ribs is sufficient to support every turn crossing the spacer and still allow the free passage of oil through the spacing strip. By properly arranging these spacers they can be made to direct the flow of oil into and out of the ducts along natural stream lines.

The proper ventilation and insulation of a transformer is equally as important as the adequate mechanical support of the winding. The system of bracing used in these transformers is particularly interesting, in that in spite of the substantial construction used, the other vital factors of ventilation and insulation have not been impaired in the least. Over 70 per cent of the area of each coil lies along a vertical duct in which direction the resistance to the flow of oil is a minimum. The velocity of oil flow under these conditions is very high and the swerving oil stream by its vigorous action scours off the stagnant film of oil adjacent to the coil itself, and thereby reduces the temperature difference between the copper and the oil. This temperature drop at the surface of the coil is one of the most important elements of temperature difference going to make up the total difference in temperature between the windings and cooling water. It falls into that division of the temperature rise which responds almost instantly to changes of load and therefore has a most important part in determining the ability of the transformer to carry overloads.

Discussion

QUEENSTON—CHIPPEWA DEVELOPMENT OF THE HYDROELECTRIC POWER COMMISSION OF ONTARIO (Gaby); DESCRIPTION OF THE 45,000 Kv-a. QUEENSTON GENERATORS (Barns and Bowness); DESIGN OF 45,000 Kv-a. GENERATORS, QUEENSTON PLANT (McCarty and Hart); FEATURES OF MAIN POWER HOUSE TRANSFORMERS FOR QUEENSTON PLANT (Price and Skinner).

Niagara Falls, Ontario, June 27, 1922

B. A. Behrend: It is instructive to note in connection with the design and construction of these large water-wheel generators installed as Niagara Falls, that the earliest units, which were rated as 5000-h.p. units, and which operated at 250 rev. per min., installed at the powerhouse of the Cataract Construction Company, as it was then called, were made with externally revolving fields, of the "umbrella" type. The field ring consisted of a large nickel steel forging, against which the solid pole pieces were bolted.

The speed of 250 rev. per min. was retained for all units from the earliest date of installation up to 1907, when the new units installed at the powerhouse of the Niagara Falls Hydraulic Power & Manufacturing Company's plant were projected with a capacity of 7500 kw. at 300 rev. per min.

Following the precedent, the first unit of this type was designed by the speaker with a nickle steel rotor, and a full description of this generator was given in the A. I. E. E. Transactions of June 1908. During the over-speed test, the first generator furnished to the Niagara Falls Hydraulic Power & Manufacturing Company was totally destroyed, the wreck appearing similar to the recent wreck of the 15,000 kw. generator at the Ontario Power Company's plant. The generator which was destroyed at the latter plant was designed and built by another manufacturer, with a cast steel rotor.

A careful examination of the fractures of the nickel steel forgings and exhaustive tests convinced me that large forgings of any kind are unreliable. They are subject to internal stresses, which are unknown, and which could be relieved only by thorough annealing, but the annealing process itself is inimical to the molecular formation of alloyed steels, even if it were possible uniformly to distribute the heat of the annealing furnace through all parts of a large mass of steel. It must be remembered in this connection, that it is customary for pieces to be heat treated to be supplied with holes, if possible, so that uniform penetration of heat can be secured. Such center holes are not practicable in electric generators, as the removal of the metal in the center leads to the doubling of the stress, on account of the redistribution of radial and tangential stresses, resulting in tangential stresses only. This matter was discussed by me in 1917 at Philadelphia, and is recorded in the A. I. E. E. Transactions, Vol. 36, p. 883. The speaker is firmly convinced from vast experience, extending over more than a score of years, that the use of large steel forgings is to be deprecated, and that the safest construction can be obtained by discarding totally these large forgings, and using steel plate construction instead.

The first large generating unit operating at 750 rev. per min., and generating about 10,000 kw. was designed by the speaker in 1904, and built by the Bullock Electric Manufacturing Company for the Brooklyn Rapid Transit Company. The modern designs of steel plate rotors differ very little from this earliest prototype. Where it is possible to use a shaft, the plates are made with holes, but where it is not possible to use a shaft, the plates are bolted together with through-bolts. The journal ends are fastened to the rotors in a manner first shown to be most effective by Delaval, in his early steam turbines. The construction is now used generally elsewhere, and has been found thoroughly reliable.

The thirteen generators now operating at the powerhouse where the 7500 kw., 300 rev. per min. generator was installed in 1908, have been designed with plate rotors, the plates being made of ordinary open hearth-carbon steel, carefully heat treated, so that the steel is thoroughly ductile. Samples from these plates, which are a little over two inches thick, have been bent cold flat through an angle of 360 deg. without showing seams or fractures on the outside.

B. T. McCormick: About fifteen years ago the companies manufacturing wheel type generators paid very scant attention to the stresses at overspeed and the possibility of the destruction of a machine as a result of a run-away. Suddenly a machine flew to pieces. This was soon followed by a number of similar accidents in different parts of the country and served to awaken the manufacturers to a realization of a serious weakness in their designs and led them to make a close study of the stresses involved, and the suitability of different materials.

The design of a machine to safely stand a run-away involves two main issues; to determine the stresses accurately, and to obtain a suitable material, the strength of which is definitely known.

The method of calculation must give a true measure of the stresses actually induced. If there is any doubt as to the accuracy of the method, the error should at least be on the safe side. Many of the stresses, on careful consideration, are found to be of a much more complicated nature than was first supposed, and of far greater magnitude. Stresses that at first seemed to be simple tension are really composed of a bending moment, a shear and a tension combined.

The material must be one of uniformly good structure throughout; one that is free from local weaknesses. To know that the material is uniform and to be able to rely on it, is even more important than very high elastic limit.

Rotors built of rolled steel disks of boiler plate mounted on the shaft have been found very satisfactory; also spiders composed of several steel castings side by side. If the castings are properly annealed and enough test pieces are obtained from various parts of the structure, as an index to its strength and uniformity, this construction is very reliable. For uniformity of structure there is no doubt that the laminated field ring is the most reliable. Such a structure is so finely divided that if any weakness exists, it will be so localized that it cannot affect the strength of the ring as a whole. This ring is usually mounted on a cast steel spider and care must be taken that the expansion of the ring at overspeed does not overstress either the arms or the dove-tails of the spider, furthermore, the design must be such that expansion at overspeed does not cause it to become loose on the spider.

W. J. Foster: I agree with Mr. Behrend that it is very important that the castings for the steel forgings be selected and tested carefully. Mr. McCormick has just remarked that about fourteen years ago there was an epidemic of machines flying to pieces. That is rather news to me, although I ought to know about such cases. I do remember happenings in two or three places, one of which our Chairman has referred to. Others occurred on the Pacific Coast, about the same time.

In connection with the idea of the last speaker, who mentioned the fact that the laminations are built up, a great number of them, so that if one is weak, the situation can be saved by its neighbors, I desire to call attention to the fact that the same principle has been carried through the designs of rotors of the multiple wheel type.

I desire to state that certain plate rotors for generators of high centrifugal stresses, involved much study and the testing of a model in the laboratory to guard against such troubles as opening at the shaft on the inner edge of the disk, a trouble which was encountered about that time in the construction of certain steam turbines. In the case of these generators a satisfactory design was obtained by cutting out holes in such manner as to leave material of the proper section to stretch sufficiently to prevent the trouble that would otherwise start at the shaft. The point I wish to make is that there are problems involved in plate construction, as well as in castings, and it is well, as Mr. Behrend has pointed out, to spare no pains to select the proper construction. Often castings should not be used but a plate or laminated rotor.

R. B. Williamson: A prominent feature of the two Queenston generators is the large fly-wheel effect as compared with other machines of comparable size. The fly-wheel effect of 21,000,000 lb. ft.^{2} is much larger relatively than that of the 32,500-kv-a. machines in the No. 3 plant of the Niagara Falls Power Company. The latter generators operate at 150 rev. per min. and have a fly-wheel effect of approximately 10,000,000 to 12,000,000. Thus taking into account the relative outputs and speeds in the two cases the Queenston machines have relatively about twice as much fly-wheel effect as the 32,500-kv-a. units.

The amount of fly-wheel effect to be put into a generator is something that must be determined for each case, taking into account the hydraulic conditions. The fact remains, however, that fly-wheel effects are frequently specified that are very much higher than the normal design of the generator would give. In order to obtain these large fly-wheel effects there has been a tendency in some cases to build generators on a larger diameter of rotor than was necessary from the standpoint of electrical design. This makes it more difficult to take care of overspeed stresses and has a decided bearing on the question of rotor construction.

While it is true that cast steel and forged steel rotors have failed in some instances, it is also true that there have been failures of laminated rotors. Not only must the materials be properly selected for a given case but the mechanical design must be such that the allowable stresses for the given material will not be exceeded. In the case of very large machines, a cast steel rotor has the advantage that it can usually be put together and tested for overspeed at the factory, after which it can be disassembled for shipment. With a large laminated rim this would necessitate stacking and unstacking and the test would be of doubtful value. It is true that there have been some accidents with cast steel and other types of rotor but if care is taken to design the rotor so that the stresses at overspeed are kept to within half the elastic limit of the material and the form of the castings made, in consultation with the steel founder, so that the finished product will be sound, thoroughly annealed and free from shrinkage strains, there is no reason why entirely safe rotors cannot be made; in fact very large numbers of them have been made and have been in successful operation for years.

F. D. Newbury: In two papers describing similar generators it is interesting to observe the differences in design and construction; in other words, how different designers have met the same problem.

The major difference in construction is found in the rotor material. In the generator described by McCarty and Hart, the rotor wheel (to which the poles are attached) consists of a single relatively light steel casting consisting of a hub and arms but without a rim. The rim is built up of 1/16 inch sheet steel punchings. In the generator described by Barns and Bowness the rotating part in made up of seven cast steel wheels placed one over the other on the shaft. It would be impossible to obtain a single satisfactory steel casting for the entire rotor. Barns and Bowness have used steel castings but have subdivided the rotor into as many castings as they considered necessary to secure sound castings. McCarty and Hart have abandoned the cast material entirely (so far as the rim is concerned) and have replaced it by a laminated construction that eliminates the question of unreliability. The laminated rim requires more material (on account of the radial joints in the rim) and more labor, but these are offset, to some extent, by the lower cost of sheet material as compared with castings. In the present case, however, the flywheel effect specified for turbine speed regulation required two additional cast steel sections in the Barns-Bowness design so that in this case, the laminated construction has an advantage, not only in potential reliability, but in rotor cost.

A second difference is found in the type of coil bracing. In one generator the outer layer of coil ends is roped to two rings; in the other, both layers of coils are bolted to cast iron brackets. The generators also differ in type of coil insulation. In the generator described by McCarty and Hart the straight parts of the coils (embedded in the core) are encased in a rigid mica wrapper while the exposed coil ends are insulated with a flexible bond between wires and a flexible tape insulation. The other generator has a flexible tape insulation throughout the entire coil.

In one generator the upper supporting bracket is cast steel and in the other cast iron. The advantage of cast steel is greater strength permitting the use of a relatively shallow structure. However, the necessity for small deflection limits the stress in cast steel to a low value so that full advantage of the greater strength of cast steel cannot be taken. Moreover, cast steel is more expensive per pound and is considerably more difficult to handle in the foundry. There is more likelihood of defective castings and the greater chance of porosity that will lead to oil leakage from the thrust bearing pot.

O. D. Wood: There is one point in the paper on transformers that is not entirely clear, namely, the bracing of the winding against vertical forces resulting from possible displacement.

It is known that in any coil arrangement, if the magnetic axes do not coincide there exists a force tending to slide one coil or a portion of a coil with respect to the other winding. Thus, if concentric cylindrical coils are not symmetrically arranged, one coil tends to slide with respect to the other, and must be braced against such movement. Bracing is provided to guard against such a movement in concentric windings.

In interleaved windings, if the coils are not symmetrical there will exist a force tending to displace the coils as a whole or portions of the coil with respect to one another.

If the coils are circular this force is resisted by the tensile strength of the conductor because the coil is of circular section.

If the coils are not circular, but rectangular, as in the shell type, this force tends to blow out one coil and to collapse the other coil towards the core. Such a force is resisted by the iron on the coil legs, but if there is no bracing on the coil ends against movement away from the core, this force will tend to cause one of the coils to become semi-circular and to collapse the other on the bracing against the core. It would seem that it is practically impossible to obtain absolute coincidence of magnetic centers even with coils of the same dimensions, but it should be much more difficult in high-voltage transformers of the interleaved style where the primary and secondary coils are usually of different dimension. In fact, it is hard to determine in such unsymmetrical coils where the magnetic center is, so that it can be stated with some degree of assurance that there will always exist a force tending to distort the coils.

Furthermore, in any event where the coils are of different dimensions there exists a force on the wider coil tending to distort it due to the curvature of the leakage flux, *i. e.* the leakage flux is not in the straight line through the leakage gaps, but curves away and some of the flux passes through the outside turns of the coil.

The analysis on page 455 regarding the effect of opposite coil ends, shown in Figures 7A and B, should be influenced by the modifying effect of the core. Under absolute short circuit the full core flux passes through the leakage gaps, yet this flux moves into the core at every coil group, and therefore modifies the condition outlined in these figures.

W. M. Dann: It seems only a few years ago that someone made the prediction that we should have transformer banks with a rating of 50,000 kv-a., and now we have them at Queenston, and they are used on a low frequency which makes them physically much larger than they would be if used on 60 cycles. In Pittsburgh, there are banks of transformers with a rating of 70,000 kv-a. in operation, but they are somewhat smaller than Queenston transformers, because they are used on 60 cycles.

Transformers of this capacity are simply an extension in size over those that have gone before, and the problems of how to insulate them and how to cool them, and how to make them strong enough mechanically to be unharmed by the mechanical forces due to short circuits are bigger problems, but problems of the same kind that have been solved with smaller units.

Insulation troubles in general are rare and generally speaking the manufacturers are ready to insulate their transformers for any possible commercial voltage. The problem of carrying off the heat from the windings in a big transformer is not particularly simple, but it is a problem which is being successfully solved. The efficiency of these Queenston transformers is very high, slightly under 99 per cent at full load, and yet this means losses of about 175 kw. in the transformer. Most of this loss is in the windings. This means that the construction must include an efficient system of ducts to carry this heat away to avoid an abnormal temperature rise at any point. An illustration used in the paper shows a system of ducts which permit the oil to flow vertically upward, which is its natural direction. The curved strips allow the oil to come into contact with every conductor in the coil. The ribbed spacers at the tops of the coils create an open construction which undoubtedly is an important factor in reducing the temperature of the windings at these points which are naturally the hottest parts of the windings.

Perhaps the most important problem with these big transformers is to make them strong enough to withstand the mechanical forces which are present in the windings due to the action of the leakage field on the conductors. There are a good many ampere turns in transformers as big as these, even with only the normal full-load current flowing and the mechanical forces are going to be present as long as we have leakage. The mechanical forces at full load would not be negligible if they were not distributed over quite an area so that the forces in pounds per square inch are low. It is under abnormal conditions such as at the time of short circuit that these mechanical forces become formidable.

This feature of the design of large transformers calls for the greatest care on the part of the designer. As I said before, the mechanical forces are going to be present as long as we have leakage fields cutting current carrying conductors and they will appear as a stress in the materials. This is independent of what kind of construction is used. In a transformer with interleaved coils for instance they will appear, in a shell-type transformer, in the form of bending moments at the tops and bottom of the coils and in a core-type as a crushing force and they must be restrained by the coil bracings.

In a core-type transformer with concentric coils they appear as a tensile strain on the conductors and they must be kept within the tensile strength of the copper.

The vertical components spoken of by the authors depend upon how closely the magnetic centers are made to coincide when the coils are assembled and the tendency for the coils to move if there is a failure to make the centers coincide exactly is present in any type of transformer.

The mechanical forces depend upon ampere-turns and a great deal can be accomplished in reducing them by proportioning the ampere turns per group properly. If the grouping of the coils is done carefully the forces can be kept within bounds and unbalancing among the groups can be minimized by locating taps carefully. If all of these things were not given careful attention, it would be an easy matter to produce a design in which the mechanical forces would exceed the bending and crushing limits of the materials used. The diagrams in the paper show that the coil grouping in the Queenston transformers was carefully worked out and attention was paid to the arrangement of the taps to keep the forces to a minimum under the worst conditions.

The authors have shown in quite a simple way that the forces affecting the coils are practically independent of the shape of the coils because those components which tend to distort them are first of all negligible compared with those which tend to separate the coils from each other, and second they practically neutralize each other leaving effective only those forces which tend to make the coils move as a whole. These forces can be calculated and it is a comparatively easy matter after designing for minimum stresses to apply the bracing necessary to take care of the forces. A section of the paper describes how this bracing is applied.

We are told that the ultimate capacity of the Queenston Station is to be between 600,000 and 700,000 kv-a. This stimulates the imagination to think of the tremendous things that might happen in time of trouble. Even with one generator and one bank of transformers connected and used as a unit, the short-circuit kv-a. capacity could be over a quarter of a million kv-a. and it speaks well for the art that transformers can be designed and built without any misgivings as to their standing up successfully under the worst short-circuit conditions that can possibly occur.

B. A. Behrend: So far as I am aware, there are no cases on record where machines designed with steel plate rotors have gone to pieces. However, there are numerous cases on record, where steel forgings and steel castings have been wrecked, and it is evident that it is the paramount duty of the designer to eliminate the elements of chance in the design and construction of these large units. The element of chance is greatest, where steel forgings are used, next greatest, where steel castings are used, and the least, where rotors are built up of steel plates. There is no question about the fact that it is possible to construct electric generators with either steel forgings or steel castings, but the fact cannot be denied, that the unknown quantity is greater in this case than it is when dealing with moderately thick plates, the structure of which is thoroughly known, which can contain no blow holes, no piping, no shrinkage stresses, and in which the material is subjected to stress in the direction in which its ductility is a maximum.

R. A. McCarty: From the papers presented and the subsequent discussion, it seems to me to be rather generally recognized among designing engineers that there is a proper field in generator construction for the use of both the built up and the cast steel types of rotor designs. As one speaker pointed out, many satisfactory machines have been built with both constructions. It, therefore, appears that the only important matter on which there is any serious disagreement, relates to the exact location of the dividing line which separates the two classes of machines in which the use of the different types of rotor should be employed. Since, as in all engineering work, the application of either design will vary, depending on the experience of the particular group of engineers concerned, it is not to be expected to find the various manufacturers following a common practise, there being no common experience. While we would not presume to take the position that our machine classification which fixes the type of rotor construction is the only correct one, I do want to emphasize the fact that in following that classification our record, contains no single case of which I am aware, of any machine of either construction going to pieces.

B. L. Barnes: I think that we are greatly indebted to Mr. Behrend for giving us the very interesting review of his experience as a pioneer in the design of large high-speed rotor construction. I think that it is generally accepted that the plate construction whether in thin laminations or boiler plate is preferable to the forged steel construction for large machines, but there is also a legitimate field for the employment of the cast steel construction.

As pointed out by Messrs. McCormick, Foster and Williamson each type of construction must be treated according to its own peculiarities, and while a given type is applicable in some machines, yet due to difficulties in manufacture it is not suitable for other machines. For instance in the case of a large generator the laminated rim construction involves the manufacture of very large sheet segments which are ordinarily made by only one or two punch press operations, limited in number in order to realize the economy peculiar to this type of construction. This involves some very nice problems in the designs of the punch and die and the punch press to handle sheets of sufficient thickness to insure ample stiffness, especially in the pole dovetail parts, and it is quite conceivable that in order to use segments of sufficient thickness the number of operations would be increased to such an extent that the economy of cheaper material is more than offset by the increased labor cost. In addition to the advantage mentioned by Mr. Williamson of being able to make overspeed tests on large rotors at the factory the cast steel construction also permits giving each part a careful balance to insure a good running balance of the completed rotor. Nor is there the danger of the balance being disturbed after a long period of operation which might result from the gradual shifting of the punchings to take a permanent seat on the through bolts and dowels.

In reference to Mr. Newberry's comparison of the two types of construction as regards the fly-wheel effect, I wish to explain that definite restrictions were placed on us by our customer as regards the diameter of the stator frame, and if we had been permitted to increase the diameter a few inches the desired fly-wheel effect could have been obtained without the use of the extra wheel sections. As Mr. Newberry has mentioned the laminated rim construction has necessitated more material, due to the radial joints which means a greater radial depth and restriction of the air passages through the rotor. Furthermore the stresses in the laminated rim are not relieved by the arms or spokes as in the case of the cast steel construction with the rim, spokes and hub cast as one piece.

In reference to Mr. Newberry's comparison of cast steel and cast iron upper bearing brackets, it should be noticed that the relatively shallow bracket obtained in cast steel has been taken advantage of for draining the oil pan of the upper guide bearing over the top of the stator windings instead of using a rotating pan on the shaft and draining the oil down through the rotor. Furthermore on the basis of a given deflection a bracket can be designed for cast steel of sufficiently smaller weight than for cast iron to overcome the disadvantage of greater cost per pound, and at the same time obtain a much greater factor of safety. We have experienced as much trouble due to porosity in cast iron construction as in cast steel.

Questions Relating to Standards of Rating, with Particular Reference to Large Machines Using Class B Insulation

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FOR the past two years the Standards Committee has been studying the present rules concerning the temperature limits of Class B insulation and the detector method of temperature measurement, as applied to large machines, and related subjects.

The Electric Machinery Committee of the Institute has suggested that an opportunity for general discussion of these questions be given members of the Institute and this meeting devoted to machinery rating and temperature limits is the result.

This paper is intended to bring to the attention of members desiring to contribute to this discussion some of the questions that are before the Standards Committee.

This statement, it should be understood, is unofficial and should be considered only as an individual expression of opinion where any opinion is expressed or preference shown for one proposal over another.

BASIC PRINCIPLE OF RATING

The principle employed in the A. I. E. E. Standards for determining the limiting temperature rises as a basis for rating is the so-called hottest-spot principle. The application of this principle in any particular case involves the determination of two quantities or figures; the limiting safe temperature of the insulation employed, and the difference between the hottest-spot temperature and the highest temperature it is possible to measure by the designated commercial method. Both of these figures are difficult to establish and in few, if any, cases can they be established to the satisfaction of everyone. As a matter of fact, agreement on most values of limiting temperature rise in use has been reached by reason of general experience, and current practise, rather than solely by the method set forth in the first chapter of the A. I. E. E. Standards.

There are two methods of approach in arriving at the limiting observable temperature rise: The hottest spot method, that in theory, at least, is scientific in that it is based on the determination of facts; and the direct discussion of temperature rise itself, without the consideration of intermediate steps. This second method is one of negotiation and compromise, and is as far from the usual methods of engineering as are the methods of the "old diplomacy." However, both methods have their advantages and limitations, and probably neither should be used alone. Whichever is considered *the* method, the other should be used to check the reasonableness of the result.

It has been suggested that the "hottest-spot" method or principle, as stated in the A. I. E. E. Standards, should be made less rigid in its application.

It has even been suggested that the complete subject matter relating to this principle be eliminated from Chapter I. A less radical suggestion is that the specific figures or values of conventional allowance and limiting observable temperatures and rises be omitted from Sections 1003, 1006 and 1009. This proposal also contemplates the elimination of specific values of conventional allowance from later chapters of the Rules, publishing only the final result—the limiting temperature rises.

A strong argument in favor of this change is the growing appreciation that it is impossible to establish single values of conventional allowance for all values of limiting temperature (for the various insulation classes) and for the various applications of each method of temperature measurement. If values of conventional allowance are to be retained in Chapter I, it will be necessary to give different values for the temperature limits of Class A insulation and Class B insulation, and to make it clear that the stated values are subject to change in specific applications. Under these conditions, the matter becomes more complicated and confusing, and it is more difficult to establish reasonable values, even for purposes of illustration.

This suggestion of omitting figures from Chapter I would work out somewhat as follows:

Section 1003. The specified differences by which the observable temperatures shall be assumed for purposes of standardization to be lower than the hottest-spot temperatures shall be designated the *conventional allowance.*

The conventional allowance depends on the method of temperature measurement, on the structure of the machine or part, on the limiting temperature rise and on a large number of design factors. Values of conventional allowance can be established only when limited to a specific method of measurement, to recommended applications of that method and to a specific value of limiting observable temperature rise.

Section 1006. This paragraph may be omitted, as it seems unnecessary to devote a separate section to the limiting observable temperatures, since they constitute merely an intermediate step in arriving at the limiting observable temperature *rises.*

Presented at the Annual Convention of the A. I. E. E., Niagara Falls, Ont., June 26-30, 1922.

Section 1009. The limiting observable temperature rises are obtained by subtracting the conventional allowances from the limiting hottest-spot temperatures (to obtain limiting observable temperatures), and by subtracting the standard ambient temperatures of reference from the limiting observable temperatures.

Values of limiting observable temperature rise for specific cases are set forth in later chapters.

It has also been suggested that Chapter I be designated "Introduction" instead of "General Principles," and that the section numbers be omitted. This would emphasize the general nature of this chapter, and still further separate it from the practical or working Rules given in later chapters.

LIMITING TEMPERATURES FOR CLASS B INSULATION

In the present standards, this limit is 125 deg. cent., with the permissive value of 150 deg. cent. as given in Footnote 2, Section 1005:

> The Institute recognizes the ability of manufacturers to employ Class B insulation successfully at maximum temperatures of 150 deg. cent., or even higher. However, as sufficient data covering experience over a period of years at such temperatures are at present unavailable the Institute adopts 125 deg. cent. as a conservative limit for this class of insulation, and any increase above this figure should be the subject of special guarantee by the manufacturer.

At its meeting of November 5, 1920, the Rotating Machinery Subcommittee presented to the Standards Committee the following report:

> It is the sense of the Subcommittee on Rotating Machinery that the accumulation of data and experience since the present American rules concerning the hottest spot temperature limit of Class B insulation were first adopted warrants it in favorably considering the adoption of a hottest-spot limiting temperature for Class B insulation of approximately 150 deg. to 160 deg., but that a specific recommendation be deferred until investigations now under way and in prospect shall have been completed.

The Standards Committee received this report and circulated it to the members of the Committee for their consideration. At its meeting held January 17th, 1921, the report was accepted and transmitted to the U. S. Committee of the I. E. C. for their information and use abroad. During 1921, the Subcommittee conducted tests (referred to in another paper at this convention) and at the meeting of the Standards Committee, held Feb. 17th, 1922, presented the following definite recommendations, which were forecasted in its preliminary report of Nov. 5, 1920:

The Subcommittee proposes the following temperature limits for large machines with Class B insulation:

Stators: By detectors located between two coil sides:			
Hottest-spot limit	150	deg.	cent.
Conventional allowance	20	"	"
Total observable temperature	130	"	"
Air temperature	40	"	"
Limiting temperature rise	90	"	"
Rotors: By resistance of the winding:			
Hottest-spot limit	150	deg.	cent.
Conventional allowance	10	"	"
Total observable temperature	140	"	"
Air temperature	40	"	"
Limiting temperature rise	100	"	"

These recommendations were brought forward at this particular time because of the plans of the I. E. C. to hold a meeting for the discussion of rating in May, 1922.

The Standards Committee adopted its Subcommittee's recommendations, subject to confirmation at its annual May meeting. In response to requests for time for further consideration, the Committee has deferred final action until May 1923.

The recommendations of the Subcommittee for stator temperatures represent a compromise between the lower and higher temperature limits of the present Standards, if observable temperature rises are considered. The present rules provide for a conventional allowance of only 5 deg., while the recommended value is 20 deg. This results in 15 deg. lower value of the rise with the same hottest-spot limit. The limiting temperature rises in the present rules and in accordance with the Subcommittee's recommendation are as follows:

Present Rules:			
With 125 deg. hottest spot limit	80	deg.	rise
With 150 deg. hottest spot limit	105	"	"
Proposed Rule	90	"	"

SEPARATION OF PERFORMANCE STANDARDS FROM TESTING AND OPERATING INSTRUCTIONS

To make the use of the Standards more convenient and to avoid the confusion of fundamentals with less important matter, it has been suggested that the things of first importance—the rules relating to the rating and performance of apparatus—be separated from the less important subject matter relating to testing methods, operation and methods of calculation.

This separation may be accomplished by placing these two kinds of material in different parts of the book or by printing the more important material more prominently.

In this connection, it has been suggested that there be included in each chapter relating to a specific type of machinery or apparatus a concise statement, generally in tabular form, of all values of limiting temperature rise that have been established by the Standards. In connection with rotating machinery, there are a number of sections in the Rules, usually stated as exceptions, that require interpretation before definite values of temperature rise can be arrived at. Table 400 (to be included in Chapter IV) is suggested to cover this proposal in the case of rotating machinery. The addition of this table to Chapter IV makes unnecessary Table 200 in Chapter II.

Other chapters in the present Standards contain similar tables of temperature rises such as, for example, Tables 501 and 502 for railway motors and Table 601 for transformers.

APPLICATION OF THE EMBEDDED DETECTOR METHOD OF TEMPERATURE MEASUREMENT

The present rules require the use of this method in all machine stators with cores having a width of 50 cm. (20 inches) or over, and in all machines of 5000 volts

TABLE 400—TABLE OF LIMITING OBSERVABLE TEMPERATURE RISES

For machines for operation in locations where the ambient temperature will not exceed 40 deg. cent. for air.[1]

	ignation Number	Items			Method or Methods of Measurement Required	Limiting Observable Temperature Rise		
						Class *O* Insulation	Class *A* Insulation	Class B Insulation
WINDINGS ON STATORS	1	Insulated windings other than 2-3-4	Windings on stators with cores of less than 50 cm. (20 inches) length if voltage is less than 10,000 volts.	Open Type	1	35	50	
					or 2	40	55	
				Enclosed Type	1	40	55	
					or 2	45	60	
			Armature winding on stators with cores of not less than 50 cm. (20 inches) length; also on stators of all machines of 10,000 volts and over.	With two coil sides per slot	3 *a*	No application		
				With only one coil side per slot		No application		
	2	Single layer field windings with exposed surfaces uninsulated and cast copper windings		Open Type	1	45	60	
				Enclosed Type	1	45	60	
	3	Wire field windings		Open Type	1	35	50	
					or 2	40	55	
				Enclosed Type	1	40	55	
					or 2	45	60	
	4	Short-circuited insulated windings			1	45	60	
WINDINGS ON ROTORS	5	Windings in slots such as d-c. armature windings and wound rotors of induction motors		Open Type	1	35	50	
					or 2	40	55	
				Enclosed Type	1	40	55	
					or 2	45	60	
	6	Single-layer field windings with exposed surfaces uninsulated			1	40	55	
					or 2	45	60	100
	7	Wire field windings			1	35	50	
					or 2	40	55	
	8	Field windings of turbine type generators			2	No application		100
	9	Short-circuited insulated windings			1	45	60	

or more, if rated over 500 kv-a. regardless of core width.

It is proposed to retain the 20-inch core limit, but change the voltage limit to 10,000 volts. The exact wording of this proposal is given under Item 1, Table 400.

The investigations of the Rotating Machinery Subcommittee have shown that the differences between winding temperatures, inside and outside the core and inside and outside the insulation of the embedded portion of the coils, are small in machines of less than 20 inches core length and of less then 10,000 volts, as these machines are ordinarily designed. For these machines, therefore, the thermometer or resistance methods of measurement are adequate.

The opinion exists, in some quarters, that the 20 inch core limit is too low. This results in turbogenerators as small as 500 kw. being equipped with embedded temperature detectors, and experience has shown that, in such small machines, there is little, if any, demand on the part of users, for this method of measurement, either for test or for regular operation. Opinion, abroad, is also in favor of a considerably higher limit in size before this method becomes applicable. If a change were made to 40 inches, the 1500-kw. 3600-rev. per min. turbo-generator would be about the smallest generator in which the detector method would be used.

The purpose of this paper is, as stated in the beginning, to stimulate discussion of the general subject and to invite the opinion of Institute members on the proposals that are referred to. It will be of value and of considerable assistance if a large number of written discussions are brought out. Written discussions sent in after the meeting will also be of service to the Standards Committee (if the author may presume to speak for the Committee) in the consideration of these matters during the coming Institute year.

Discussion

For discussion on this paper see p. 529.

Probable Values of Conventional Allowance for A-C. Generator Stator Windings

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THE principle employed in the A.I. E. E. Standards for determining the limiting temperature rises as a basis for rating is the so-called hottest-spot principle. The hottest-spot temperature is the bench mark or original point of reference and the limiting observable temperature is derived from it by subtracting a temperature that represents the difference between this temperature and the highest temperature that it is possible to measure by commercial methods. This difference is known in the A. I. E. E. Standards, as the "conventional allowance."

This basis for determining limiting observable temperatures can scarcely be criticized on theoretical grounds. It has been criticised, however, and with reason, because of the practical difficulties attending the evaluation of the conventional allowance. These practical difficulties have been greatly increased by the conception of the conventional allowance as an attribute of the method of measurement alone, resulting in a single conventional allowance for each recognized method of measurement.

Experience in building up standards under this principle has shown that it is impossible for a single value to satisfy all the practical situations arising. The conventional allowance with a certain method of measurement will vary with the total temperature or temperature rise; this has led to the suggestion that different values of conventional allowance be assigned for the different temperature limits of the different classes of insulation. But, even with a given method of measurement and a given limiting temperature the proper conventional allowance may still vary considerably because of the widely different conditions existing in different applications. For example, a conventional allowance for the thermometer method of measurement (with Class A Insulation temperature limits) may vary considerably in these several applications: A small induction motor stator winding, a large wire-wound shunt field coil, or an air-blast transformer winding. Or, to consider another class, the conventional allowance for the resistance method of measurement (with Class B insulation temperature limits) may vary considerably in a turbine type generator rotor winding and in a relatively small railway motor armature winding.

A consideration of these facts has led many engineers away from the idea of a single value of the conventional allowance applicable to a given method of measurement toward the idea of a conventional allowance associated with a single particular application. The former conception made the values of conventional allowance general in their application and the numerical values naturally became a part of the principle. The latter conception makes the values limited and specific in their use and divorces them from the general principle; this strengthens both the principle and the application of the principle to practical cases.

The work described in this paper has been based on this second conception of the conventional allowance. It has been attempted to determine experimentally the value of the conventional allowance for this particular method of measurement when applied to a given class of alternating-current machine stator windings for given temperature limits.

This experimental work has been of two kinds: First, the measurement in machines of various sizes and voltages of copper temperatures by detectors inside the coil insulation) and of "observable" temperatures (by detectors located between the two coil sides in a slot) thus determining, by direct measurement, the data on which values of conventional allowance can be based; and second, an investigation of the influence of various factors such as insulation thickness, eddy current losses, core length and core temperature on the conventional allowance, by using a small armature model in which these several factors can be varied conveniently.

The tests on generators have been carried out under the direction of the Subcommittee on Rotating Machinery of the Standards Committee and the author acknowledges, with pleasure, his indebtedness to the Committee for permission to publish this information. Mr. C. J. Fechheimer is responsible for the interpretation of the model test results and the development, therefrom, of the formulas for the calculation of values of conventional allowance and top-coil copper temperatures.

MODEL TESTS

In Figs. 1 and 2 are shown the details of a model designed to reproduce the temperature conditions in a radially ventilated armature core.

Thermocouples are distributed throughout the coils and core as indicated, so as to measure the true copper temperature, the temperature between coils and the average tooth temperature.

The several factors whose influence on the conventional allowance it is desired to study were reproduced as follows:

Presented at the Annual Convention of the A. I. E. E., Niagara Falls, Ontario, June 26-30 ,1922.

1. In order to imitate the conditions that obtain in a long machine, the coil ends were blocked so that the cooling of the ends by forced convection was very small. Thermocouples in the ends then showed nearly the same temperature as the copper in the embedded part, and therefore the longitudinal heat flow was negligible, thus simulating conditions that obtain at the middle of a long-core machine. The short-core machine was imitated by opening the coil ends to the ventilating air streams.

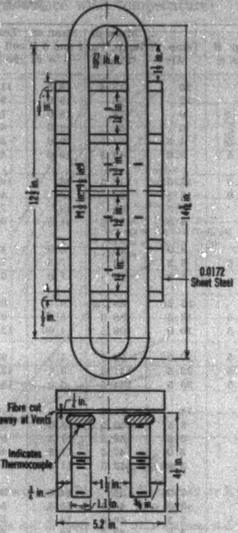


Fig. 1

Two coils, each consisting of eighty turns of 0.095-in. by 0.122-in. d. c. c. arranged 8 by 0.095 in. wide.

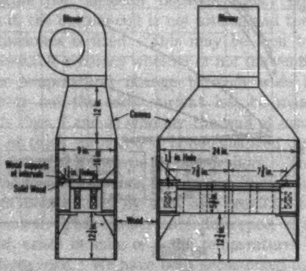


Fig. 2

2. The temperature of the iron was altered by changing the speed of the blower supplying the cooling air. By this means the iron temperature rise was changed from 10.5 to 70 deg. rise for the long-core, or from 9 to 40 deg. rise for the short-core machine, with the same current in the coils.

3. In all tests, direct current was used in the two coils. In order to imitate the influence of eddy currents the value of current in the upper coil was changed, the current in the lower coil being kept substantially constant throughout the tests.

4. The coil insulation was nominally for 6600 volt wrapper but it was crowded into a smaller space than is ordinarily used for that voltage. The wall thickness was approximately 0.11 in. Extra insulation was placed between coils, as shown in Fig. 3. The extra insulation was about 0.32 in. thick, thus making the equivalent wall thickness $\frac{0.32}{2} + 0.11 = 0.27$ in, or slightly greater than would be used for 13,200 volts. Tests were made with and without this extra insulation.

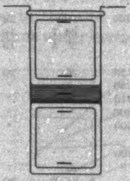


Fig. 3

Twenty eight different temperature tests were made under various conditions; the first series was equivalent to a 13,200-volt long-core generator with varying eddy current losses (varying loss ratio) and with varying core temperatures; similar series of tests were made for a 6600-volt long-core armature and for 13,200-volt short-core armatures. All temperature tests were continued until steady temperatures were attained. The test results of all runs are summarized in Table I and the results of typical runs are plotted in the accompanying curves.

Fig. 4 shows the variation in temperature rises for different blower speeds, equivalent to different core temperatures, with 20 amperes in each coil and imitating the long-core machine. (The reciprocals of blower speeds are used as abscissas in order that the curves approach straight lines). It will be seen that the maximum copper temperature and iron temperature curves are nearly parallel, indicating that although the iron temperature rise increased from 10.5 deg. to 70 deg. the drop from the copper to the iron changed but little; and this small increase was largely due to the increase in copper temperature with resistance. This relation is to be expected from the fundamentals

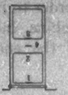


TABLE I

SUMMARY OF TESTS ON ARMATURE MODEL

Long or short core	Extra ins. bet coils	Fan rev. per min.	Amps. top coil	Amps. bot. coil	Loss Ratio = (*I*top *I*bot.)	Temp. *R* Pos 1	Temp. *R* Pos. 4 *θm*	Temp. *R* Iron *θi*	Temp. *R* Air	Mean of temp. Pos (2) & (3)	Mean of 2 and 3 H −4 = *θa*	Test top coil temp. rise Pos. 2	Test bot coil temp. r. Pos. 3
Long	Yes	150	20	20	1.	110	97	70	20	115.5	18.5	115	116
"	"	200	"	"	"	89	78	53	12	96	18.0	96	96
"	"	300	"	"	"	73	60	37	9	78	18.0	78	78
"	"	600	"	"	"	57	43	22	6	61	18.0	61	61
"	"	900	"	"	"	49.5	34.5	16.5	4.5	53.5	19.0	53.5	53.5
"	"	1400	"	"	"	40.5	24.5	10.5	2.0	43.5	19.0	43.5	43.5
"	"	300	25	20	1.56	121.5	89.5	52.5	12.5	112.5	23	128.5	96.5
"	"	1400	20	"	1.0	43	27	11.0	2.2	46	19	45	47
"	"	"	25	"	1.56	69	38	17	3.2	60	22	71	49
"	"	"	28	"	1.96	89	47	20	4.0	71.5	24.5	90	53
"	No.	1400	20	20	1.00	42	40	11	4.0	48	8.0	47	49
"	"	"	25	"	1.56	66.5	55.5	14.5	6.3	63	7.5	71.5	54.5
"	"	"	27.5	"	1.89	84.0	69.0	19	8.0	76	7.0	91.0	61.0
"	"	600	20	20	1.00	61.0	63	28	12.25	69.75	6.75	68	71.5
"	"	"	25	"	1.56	88.5	83.5	30.5	13.5	88.0	5.50	97.5	78.5
"	"	"	27.5	"	1.89	114.5	104.5	40.5	19.0	108.5	4.00	125.5	91.5
"	"	300	20	20	1.00	82.5	86.5	45.5	22.0	92.0	5.5	91.5	92.5
"	"	"	24.7	19.4	1.62	124.5	118.5	60.5	32.5	121.5	3.0	133.5	109.5
"	"	"	27.5	19.6	1.97	149.5	139.5	70.5	35.5	144.5	5.0	164.5	124.5
Short	Yes	150	20	20	1.00	66	59	40	11	71.5	12.5	70	73
"	"	230	"	"	"	55	47	30	8.5	60.0	13.0	58	62
"	"	310	"	"	"	48	41	24	6.8	52.5	11.5	51	54
"	"	400	"	"	"	44	36	20	5.0	47.5	11.5	46	49
"	"	600	"	"	"	39	31	15	3.2	42.5	11.5	41	44
"	"	1400	"	"	"	33	22	9	2.0	36	14.0	35	37
"	"	"	25	"	1.56	50	31	13	2.5	46.5	15.5	55	38
"	"	"	24.5	20.8	1.50	49.5	31.5	11.5	2.5	46.0	14.5	53.5	38.5
"	"	"	27.5	20.0	1.90	60.0	36.0	13	2.8	52.0	16	65.0	39

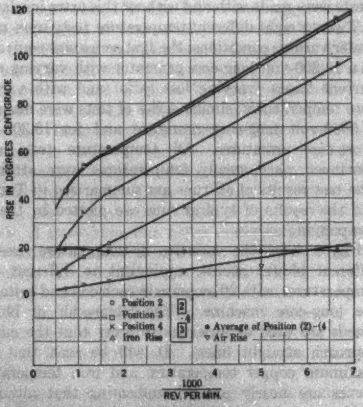


FIG. 4—TEMPERATURE RISE AS A FUNCTION OF RECIPROCAL OF FAN REV. PER MIN.

Twenty amperes d-c in both coils. Ends poorly ventilated. Long core machine. ½ in. extra insulation between coils.

of heat flow and temperature drop. This is the first important fact to be observed.

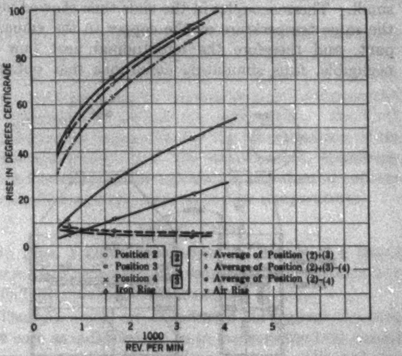


FIG. 5—TEMPERATURE RISE AS A FUNCTION OF RECIPROCAL OF FAN REV. PER MIN.

Twenty amperes d-c. in both coils. Ends poorly ventilated. Long core machine. No extra insulation between coils.

The second important fact may be noted from Figs. 4, 5, and 6 viz., the amount or velocity of cooling air has no effect upon the total temperature drop through the insulation, or on the difference between copper and observable temperatures, (if allowance is made for the increase in resistance with temperature). It follows, that changes in armature temperatures caused by changes in ventilation are not accompanied by any changes in conventional allowances.

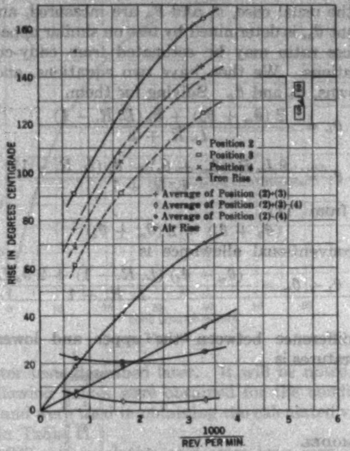


FIG. 6—TEMPERATURE RISE AS A FUNCTION OF RECIPROCAL OF FAN REV. PER MIN.

Twenty amperes d-c. in lower coil. 27.5 amperes d-c. in upper coil. Ends poorly ventilated. Long core machine. No extra insulation between coils.

The third important fact is that there is substantially a constant difference between the mean of the top and bottom coil temperatures and the observable temperature rise (detector between coils,) provided the loss in the bottom coil is not altered and the insulation thickness is fixed. This may be seen to hold with reasonable accuracy whether or not the ventilation (or iron temperature) change through wide limits; whether or not the eddy current loss be materially changed; Figs. 7 and 8; whether the wall of insulation be thin or thick (provided it is not changed during a series of tests); or if the core be long or short. This fact is interesting and of value, and to our knowledge has not been pointed out by any one previous to this investigation. This temperature difference, it should be noted, exists in spite of equal temperatures in top and bottom coils. We have been accustomed to think that under this condition of equal coil temperature, the observable temperature is equal to the copper temperature. Such, however, is not the case because there is heat flow to the slot sides from the adjacent sides of the coils and from this series of tests a measure of the temperature drop caused by this flow was obtained. Thus, (see Table I) this drop for the same current in both coils, was 18 to 19 deg. for iron temperature rises of 10.5 deg. to 70 deg., (with extra insulation between coils); and was 10.5 deg. to 13 deg. for variations in iron temperature rises from 9 deg. to 40 deg. (for no extra insulation between coils). With variations in loss ratio, for a given insulation and core length, the change in this drop is slightly greater, but still can be considered as constant with reasonable accuracy.

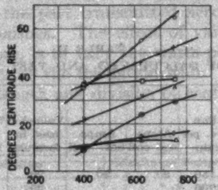
These relations are used in deriving the equations for calculating the conventional allowance. Let

θ_t = the temperature rise of the copper in the top coil

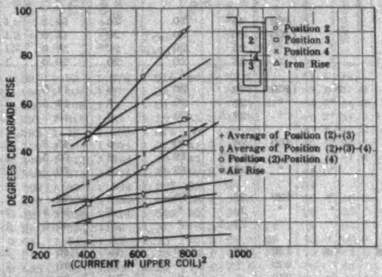
θ_b = the temperature rise of the copper in the bottom coil

θ_m = the temperature rise by detector between coil sides

θ_a = the temperature difference between the means of top and bottom coil temperatures and the temperature by detector between coils. This is equivalent to the drop in temperature due to heat flow to the slot sides (between coils) and is constant under certain conditions.



Tests at 1400 rev. per min. of fan. Twenty amperes d-c. in lower coil in all tests. Temperature rises as a function of square of current in upper coil. ¼ in. extra insulation between coils.



Ends poorly ventilated. Long core machine.

FIG. 7

By definition

$$\theta_a = \frac{\theta_t + \theta_b}{2} - \theta_m \qquad (1)$$

It is reasonable to assume that the temperature rises of the top and bottom coils above the temperature of the adjacent core teeth is proportional to the losses in these coils; the ratios of these temperature rises will be equal to the ratio of the losses. The loss in each coil is the $I^2 R$ loss plus the eddy current loss, both of which can be calculated in a given case.[1] Let this ratio of coil losses be designated by L. R. and the core tooth temperature by θ_i; then:

$$L.\,R. = \frac{\theta_t - \theta_i}{\theta_b - \theta_i} \qquad (2)$$

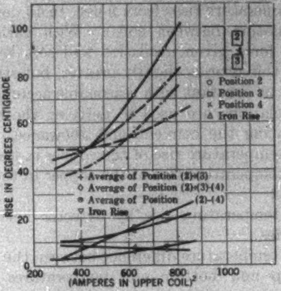


Fig. 8—Temperature Rise as a Function of Square of Current in Upper Coil

Current in lower coil constant equals twenty amperes. Fan speed constant equals 1400 rev. per min. Ends poorly ventilated. Long core machine. No extra insulation between coils.

In the usual case, θ_t and θ_m are measured, and the constant θ_a, is determined by test on similar apparatus. The loss ratio may be estimated from eddy-current calculations. We then have two equations, and two unknowns, θ_b and θ_t. Solving for them,

$$\theta_b = \frac{2\,(\theta_m + \theta_a) + \theta_i\,(L.\,R. - 1)}{L.\,R. + 1} \qquad (3)$$

$$\theta_t = \frac{2\,L.\,R.\,(\theta_m + \theta_a) - \theta_i\,(L.\,R. - 1)}{L.\,R. + 1} \qquad (4)$$

Also from (1)

$$(\theta_b + \theta_t) = 2\,(\theta_m + \theta_a) \qquad (5)$$

The conventional allowance is

$$\theta_c = \theta_t - \theta_m = \frac{(\theta_m - \theta_i)\,(L.\,R. - 1) + 2\,\theta_a\,L.\,R.}{L.\,R. + 1} \qquad (6)$$

The difference between the upper and lower coil temperatures is

$$(\theta_t - \theta_b) = \frac{2\,(\theta_m + \theta_a - \theta_i)\,(L.\,R. - 1)}{L.\,R. + 1} \qquad (7)$$

Equation (4) then gives the top coil temperature rise, and equation (6) gives the conventional allowance.

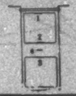


TABLE II

COMPARISON OF CALCULATED AND TEST RESULTS—ARMATURE MODEL

Long or short core	Extra Ins. bet. coils	Fan rev. per min.	Amps. top coil	Amps. bot. coil	Value θ_a used in formula	Value of θ_i in formula	Value of $L\,R$ in formula	Calc. top coil temp. rise	Test top coil temp. rise for pos. 2	Calc. bot. coil temp. rise pos. 3	Test bot. coil temp. rise pos. 3	Calc. conv. allowance θ_{ca}	Test θ_{ca} pos. (2) pos. (4)	Diff. bet. test and calc. pos. 2	same as % of pos. (2) temp. rise
Long	Yes	150	20	20	20	70	1.0	117	115	117	116	20	18	− 2	1.7
"	"	200	"	"	20	53	"	98	96	98	96	20	18	− 2	2.1
"	"	300	"	"	20	37	"	80	78	80	78	20	18	− 2	2.6
"	"	600	"	"	20	22	"	63	61	63	61	20	18	− 2	3.3
"	"	900	"	"	20	16.5	"	54.5	53.5	54.5	53.5	20	19	− 1	1.9
"	"	1400	"	"	20	10.5	"	44.5	43.5	44.5	43.5	20	19	− 1	2.3
"	"	300	25	20	20	52.5	1.56	122	128.5	97	96.5	32.5	39	+ 6.5	− 5.1
"	"	1400	20	20	20	11.0	1.0	47	45	47	47	20	18	− 2	4.4
"	"	"	25	20	20	17.0	1.56	67	71	49	49	29	33	+ 4	− 5.6
"	"	"	28	20	20	20.0	1.96	82.5	90	52	53	35.5	43	+ 7.5	− 8.3
"	No	1400	20	20	6	11.0	1.00	46	47	46	49	6	7	+ 1	− 2.12
"	"	"	25	20	6	14.5	1.56	72	71.5	51.2	54.5	16.5	16.0	− 5	.7
"	"	"	27.5	20	6	19	1.89	92.4	91.0	57.8	61	23.4	22	− 1.4	1.5
"	"	300	20	20	6	45.5	1.00	92.5	91.5	92.5	92.5	6	5	− 1.0	1.1
"	"	"	24.7	19.4	6	60.5	1.62	140	133.5	109	109.5	21.5	15	− 6.5	4.9
"	"	"	27.5	19.6	6	70.5	1.97	170	164.5	12.1	124.5	30.5	25	− 5.5	3.3
"	"	600	20	20	6	28.	1.00	69.	68.	69.	71.5	6.	5	− 1.0	1.4
"	"	"	25	"	6	30.5	1.56	102.5	97.5	76.8	78.5	19.	14	− 5.0	5.1
"	"	"	27.5	"	6	40.5	1.89	132.	125.5	89.2	91.5	27.5	21	− 6.5	5.2
Short	Yes	150	20	20	13	40	1.00	72	70	72	73	13	11	− 2	2.9
"	"	230	"	"	13	30	1.00	60	58	60	62	13	11	− 2	3.5
"	"	310	"	"	13	24	1.00	54	51	54	54	13	10	− 1	2.0
"	"	400	"	"	13	20	1.00	49	46	49	49	13	10	− 1	2.2
"	"	600	"	"	13	15	1.00	44	41	44	44	13	10	− 1	2.4
"	"	1400	"	"	13	9	1.00	35.0	35	35.0	37	13	13.0	0.0	00.0
"	"	"	25	"	13	13	1.56	50.7	55	37.8	38	19.7	24	+ 4.3	− 7.8
"	"	"	24.5	20.8	13	11.5	1.50	51.2	53.5	37.9	38.5	19.7	22	+ 2.3	− 4.3
"	"	"	27.5	20.0	13	13.0	1.90	60.0	65.0	38.0	39.0	24	29	+ 5	− 7.7

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[1] See Eddy Current Losses in Armature Conductors. R. E. Gilman, A. I. E. E. Transactions 1920; also article by S. L. Henderson, *Electric Journal*, September 1920, giving principal formulas with examples.

It remains to establish the variation of θ_a with core length, insulation thickness and rate of heat flow. This can be done from the results of the model tests and the

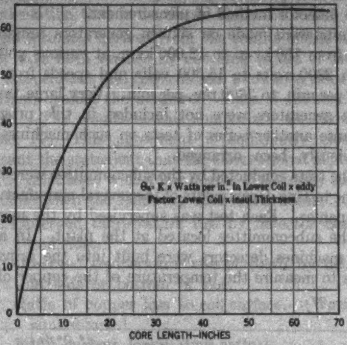


Fig. 9

generator tests described later. It will be noted that the following values were obtained for the conditions tested and were used in obtaining the calculated values given in Table II.

For 13,200-volt insulation and very long core (say in excess of 60 inches).......20 deg.

For 13,200-volt insulation and very short cores (8 1/2 inches).......................13 deg

For 6600-volt insulation and very long core.... 6 deg.

The value θ_a remains constant with varying loss ratios, varying core temperatures and with constant loss in the bottom coil as shown by the model tests.

No tests were made with varying loss in the bottom coil but a little consideration will show that the heat flow to the slot sides (and consequently the value of θ_a) will vary in proportion to the rate of heat flow from the bottom coil (or the watts per square inch of coil surface).

It is also assumed (from the fundamentals of heat flow) that θ_a is proportional to the insulation thickness. We may then write

$\theta_a = K \times$ watts per sq. in. $\times$ insulation thickness (8)

In this expression K varies with core length. In long core machines (say over 60 inches) the heat generated in the copper at the center of the core is transmitted wholly across the insulation wall to the core. As the core length diminishes a greater part of the heat generated in the copper at the center of the core is transmitted along the copper to the external coil ends and the part transmitted across the insulation wall diminishes. The effect of variation in core length, therefore, is to vary the watts per square inch transmitted across the insulation wall. The relations between core length and division of heat flow between

TABLE III

Machine Number	Rating					Core Length	Insulation thickness	Test Conditions			Data under Test Conditions						Maximum Temperature Rise					Conv. Allowance
	K. V. A.	Frequency	Volts	Amp	R. P. M.			Volts	Amp.	Power factor	Amp. per sq. in. in Conductor	Watts per sq. in. at 75° C. Top Coil	Watts per sq. in. at 75° C. Bot. Coil	Eddy current factor (Top)	Eddy current factor (Bottom)	Loss Ratio	(1) Top of upper coil	(2) Bot. of upper coil	(3) Top of bot. coil	Between coils (4)	Between top coil and tooth (5)	
1	1250	60	2300	313	300	14	0.125	2300	313	0	3410	1.02	1.00	1.02	1.004	1.016	46.6	52.7		51.4	44.5	1.3
2	1250	60	2400	300	3600	33.5	0.138	2400	300	0	2170	0.584	0.564	1.106	1.07	1.03		53.0	48.5	48.2	37.0	4.8
								2400	383	0	2770	0.950	0.920	1.106	1.07	1.04		73.5	67	68.0	44.0	5.5
3	1560	60	2200	410	3600	46	0.162	2000	451	0	1820	0.455	0.391	1.215	1.04	1.16	68.3	58.9		46.2	32.5	12.7*
4	3000	25	2300	750	750	33	0.125	2300	545	0	1860	0.400	0.392	1.02	1.004	1.015	30	32.3		32.3	25.4	0.0
								1835	753	0	2580	0.764	0.750	1.02	1.004	1.015	41.5	45.5		45.5	32.5	0.0
5	3125	62	2300	785	750	25	0.115	2300	559	0	1890	0.504	0.449	1.215	1.084	1.12	45	48.5		48.5	41.0	0.0
								1940	785	0	2600	0.991	0.886	1.215	1.084	1.12	50.5	65.0		64.0		1.0
6	750	60	6600	65.6	300	14.5	0.131	6600	58.3	0	2200	0.577	0.562	1.03	1.004	1.025	35	36		34		2.0
7	1250	25	6400	113	300	13	0.182	6400	113	0	2460	0.766	0.760	1.008	1.000	1.008	55.8	61.3		59.4	40.8	1.9
8	2450	25	6600	214	750	25	0.175	6600	180	0	2090	0.533	0.527	1.026	1.014	1.009	33	35		29	25	6.0
9	2500	60	6600	219	240	13	0.117	6600	219	0	2670	1.71	1.25	1.45	1.06	1.37	78.5	75	74	72	62.5	3.0
10	5500	60	6600	481	225	22.5	0.144	6600	481	0	1970	0.790	0.63	1.34	1.07	1.25	77.5	68.5	65	63.5	60.5	5.0
11	6000	60	6600	525	600	21.5	0.142	6600	525	0	2510	1.278	1.01	1.35	1.07	1.26	83.8	82.5	79.5	72.1	61.9	10.4
12	12000	60	6600	1050	150	33	0.165	6600	960	0	1820	0.821	0.645	1.58	1.24	1.27	78.3	72.6		64	54	8.6
13	2500	50	11000	131	750	15	0.24	0	131	s. c.	2245	0.62	0.595	1.061	1.02	1.04	38.4			29.8	28.0	8.6
										under exc.												
								11000	131	0	2300	0.814	0.756	1.186	1.026	1.15	68	76		66		10.0
14	2500	50	11000	131	750	16	0.211			over exc.												
								11000	131	0	2300	0.874	0.756	1.186	1.026	1.15		95		88		7.0
15	1250	50	15000	48	750	20		15000	48	.90							32	33	52	28	26.5	5.0
								15000	72	.95							51.5	52.5		41.5	37.0	11.0
16	3500	50	10000	203	750	27		10000	250	0							56.5	61†	60	48.5	43	12.5

In machines 1-4-5-7-8-13-15-16—10-inch resistance detectors are used; those inside main insulation are in contact with cotton covering of wires; other machines have thermocouples and couples inside insulation are in contact with bare copper. All detectors are located in center of core, lengthwise.

*Temp. affected by flux from field augmenting loss in upper coil.

†Bottom of bottom coil.

the transverse and longitudinal paths are quite complicated, but these have been investigated and the general shape of the curve is known.[2]

The curve, Fig. 9, showing the relation between K and core length has been arrived at from a consideration of these general relations, and the experimental data from both the model tests and the tests on machines. The data from the model tests with extra insulation between coils have not been used (except as an indication of the relative variation of K with core length) because of the known fact that the heat conductivity of laminated insulation varies greatly with and across the laminations.[3] With the extra insulation between coils as used in the model, the layers of the insulation were not rounded, as would be the case with coil insulation, but lay flat. See Fig. 3. Consequently the side flow of heat was greater and the temperature drop was greater than in the usual case.

TABLE IV

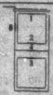
Machine No.	Core length	Value of K	Insulation thickness	Watts per sq. in bottom	Calc. value θ_a	Loss ratio	θ_m	θ_t	Calc. value θ_t	Tested value θ_t	Calc. value conventional all.	Tested value conventional all.	$\frac{[\theta\text{ (test)} - \theta_t\text{ (calc.)}] \times 100}{\theta_t\text{ (test)}}$	
1	14	42	0.125	1.00	5.25	1.016	51.4	44.5	56.8	52.7	5.4	1.3	− 7.8	
2	33.5	60	0.138	0.564	4.65	1.03	48.2	37	53.2	53	5.0	4.8	− .38	
				0.920	7.65	1.03	68.0	44	76.3	73.5	8.3	5.5	− 3.8	
3	46	63	0.162	0.391	4.00	1.16	46.2	32.5	51.6	58.9	5.4	12.7*	+ 14.2	
4	33	59.5	0.125	0.392	2.90	1.015	32.3	25.4	35.3	32.3	3.0	0.0	− 9.3	
				0.750	5.50	1.015	45.5	32.5	51.3	45.5	5.8	0.0	− 12.7	
5	25	54.5	0.115	0.440	2.82	1.12	48.5	41.0	51.9	48.5	3.4	0.0	− 7.0	
				0.886	5.60	1.12	64.0	54†	70.5	65.0	6.5	1.0	− 8.5	
6	14.5	43	0.131	0.562	3.18	1.025	34	33†	37.9	36.0	3.9	2.0	− 4.5	
7	13	39	0.182	0.760	5.40	1.008	59.4	40.8	64.8	61.3	5.4	1.9	− 5.4	
8	25	54	0.175	0.527	5.0	1.009	29	25	34	35	5	6	+ 2.85	
9	13	39	0.117	1.25	5.72	1.37	72	62.5	80	75	8.0	3.0	− 6.25	
10	22.5	52	0.144	0.63	4.7	1.25	63.5	60.5	69.1	68.5	5.6	5.0	− 8.7	
11	21.5	50	0.142	0.63	7.2	1.26	72.1	61.9	81.4	82.5	9.3	10.4	+ 1.09	
12	33	60	0.165	0.645	6.5	1.27	64.0	54.0	72.5	72.6	8.5	8.6	+ 1.3	
13	15	43	0.24	0.595	6.25	1.04	29.8	28	36.3	38.4‡	6.5	8.6	+ 6.0	
14	16	44	0.211	0.756	7.0	1.15	66	58†	74.4	76	8.4	10	+ 2.1	under exc.
				0.756	7.0	1.15	88	70†	96.8	95	8.8	7	+ 1.87	over exc.

*Temperature affected by flux from field augmenting loss. Iron temperature at bottom of slot.

†Iron temperature assumed, not given from test.

‡On copper of top of upper coil.

Note: Iron temp. not given from tests: The iron temperature rises by thermometer were increased by amounts indicated by tests on other machines. The iron temperature, as used in formula, has small influence upon the copper temperature, except when the loss ratio is high.



In equation (8) the watts per square inch refer to the bottom coil, the watts being the $I^2 R$ loss at 75 deg. cent., plus the calculated eddy current loss in the bottom coil at the same temperature, and the surface being that of the bare copper, omitting the side adjacent to the top coil. The insulation thickness is taken as one-half the difference between slot width and bare copper width.

GENERATOR TESTS

At a meeting held November 4, 1920, the Rotating Machinery Subcommittee of the Standard Committee of the A. I. E. E. arranged to make tests on generators of three different manufacturers to obtain data that would be useful in the revision of the temperature limits of large machines using the embedded temperature detector method of measurement.

Tests were made on sixteen generators ranging in size from 750 kv-a. to 12,000 kv-a. at various voltages from 2300 volts to 15,000 volts and speeds from 150 rev. per min. to 3600 rev. per min. Very large turbine type generators were not included in this program, because another series of tests on such machines had previously been arranged.

The tests conducted by the subcommittee were made in the testing departments of the several manufacturing companies. Each test was supervised by the member of the subcommittee located at the plant. In all of the machines detectors were built into the armature coils to measure the temperature of the copper of the top coil and detectors were located between coil sides. In some of the machines detectors were also located inside the insulation of the bottom coil and between the top coil and core tooth.

The essential design information and test results are given in Table III.

A word of caution may be required against using these generator tests *directly* for estimating probable or reasonable limiting values of conventional allowance or measureable temperature rise. The generators selected for test were, in six cases, of shorter core length than the limit set in the Rules for the detector method of measurement; in five cases were for low voltage; in three cases were for low frequency; and in general were of such size and characteristics that low rises and values of conventional allowance should be expected.

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[2] Longitudinal and Transverse Heat Flow in Slot-Wound Armature Coils. C. J. Fechheimer, JOURNAL, A. I. E. E., March, April and May 1921.

[3] The Thermal Conductivity of Insulating and other Materials, T. S. Taylor, *Electric Journal*, December, 1919.

The entire class of large turbo generators was intentionally excluded. But while these tests may not be used directly for determining probable limiting values, they are as good as any for the purpose employed in this paper; viz., for checking the validity of the method of calculation that is developed from the model tests.

The formulas derived from the results of the model tests have been verified by checking values of the top coil temperature and conventional allowance calculated by them against the measured values of the machines tested. The results of this comparison are shown in Table IV. This agreement is sufficiently close to warrant the statement that the conventional allowance can be calculated with a fair degree of accuracy for any machine when the following data are available:

1. Observed temperature rise by detector between coil sides.
2. Observed temperature rise of tooth by detector at side or bottom of slot.
3. Ratio of copper loss to coil surface. (Watts per square inch.)
4. Eddy current losses (loss ratio).
5. Thickness of insulation.
6. Length of core.

As might be expected, some of the test results do not check with the calculated results as closely as others.

The two units No. 4 and No. 5 show practically no difference between the copper temperature and observable temperature. These two machines are among those having ten-inch detectors inside the main coil insulation (in contact with the cotton covering on the wires) instead of thermocouples in contact with the bare copper. With thin insulation (for 2300 volts) low loss ratios and low temperature rise, the conventional allowance will be naturally low and the method of measuring the copper temperature will have a relatively large influence on the measured difference between the copper and observable temperatures.

Unit No. 3 shows a higher measured conventional allowance than can be accounted for. This is a two-pole turbo-generator and the designer explains this discrepancy by the existence of extra losses in the top coil caused by the penetration of main rotor flux into the slot.

As will be evident by considering the method of derivation, the formula for calculating the top coil temperature gives the temperature of that part of the top coil adjacent to the bottom coil. (Position 2, Table III). In generators having small eddy current losses, this is the maximum temperature of the top coil; in generators having larger eddy current losses or in which the main field flux penetrates the slots, thus producing additional eddy current losses, the temperature of that part of the top coil adjacent to the air gap (Position 1, Table III) is the maximum. This is illustrated by the following figures taken from Table III.

Unit No.	L. R.	Position 1 top of upper coil	Position 2 bottom of upper coil	Diff.
3	1.16	68.3	58.9	9.4
9	1.37	78.5	75	3.5
10	1.25	77.5	68.5	9.0
11	1.26	83.8	82.5	1.3
12	1.27	78.3	72.6	5.7

In the comparison between measured and calculated top coil temperatures, the test values given in Table IV are for Position 2 in every case, and this fact should be considered in drawing any conclusions as to the probable range of values of conventional allowance in practise.

CALCULATION OF THE CONVENTIONAL ALLOWANCE FOR LIMITING CASES

The only values of the conventional allowance that are of interest from the standpoint of standardization are those that exist at the limiting copper temperatures. In determining the proper value of the conventional allowance for the temperature limit of Class *A* insulation, for example, the values of the conventional allowance that exist when the copper temperature is 105 deg. are the only ones that are of interest. It is possible, then, to assume various sets of conditions (all of which result in 105 deg. copper temperature) and to calculate the conventional allowance, and, in that way, obtain a quantitative idea of the range of values of the conventional allowance at the assumed limiting copper temperature.

TABLE V

CALCULATED CONVENTIONAL ALLOWANCES

6600-Volt Insulation—105 deg. Copper Temperature.
Insulation Thickness—0.15 inch
Calculations are based on long core machines.

Top coil temp. rise	65	65	65	65	65	65	65	65	65
Core temp. rise	25	35	45	25	35	45	25	35	45
Temp. drop through ins.	40	30	20	40	30	20	40	30	20
Watts per sq. in., top	0.8	0.6	0.4	0.8	0.6	0.4	0.8	0.6	0.4
Loss ratio	1.10	1.10	1.10	1.20	1.20	1.20	1.40	1.40	1.40
Watts per sq. in., bot	0.73	0.54	0.36	0.67	0.50	0.33	0.57	0.43	0.28
θ_c	7	5.2	3.5	6.5	4.8	3.2	5.5	4.1	2.7
θ_m	56.2	58.4	60.6	55.1	57.7	60.1	53.8	56.6	59.4
Conventional allowance	8.8	6.6	4.4	9.9	7.3	4.9	11.2	8.4	5.6

TABLE VI

CALCULATED CONVENTIONAL ALLOWANCES.

13200-Volt Insulation—105 deg. Copper Temperature.
Insulation Thickness—0.25 inch
Calculations are based on long core machines.

Top coil temp. rise	65	65	65	65	65	65	65	65	65
Core temp. rise	25	35	45	25	35	45	25	35	45
Temp. drop through ins.	40	30	20	40	30	20	40	30	20
Watts per sq. in., top	0.48	0.36	0.24	0.48	0.36	0.24	0.48	0.36	0.24
Loss ratio	1.10	1.10	1.10	1.20	1.20	1.20	1.40	1.40	1.40
Watts per sq. in., bot	0.435	0.33	0.22	0.40	0.30	0.20	0.34	0.26	0.17
θ_c	7.0	5.2	3.5	6.5	4.8	3.2	5.5	4.1	2.7
θ_m	56.2	58.4	60.6	55.1	57.7	60.1	53.8	56.6	59.4
Conventional allowance	8.8	6.6	4.4	9.9	7.3	4.9	11.2	8.4	5.6

Tables V and VI show such calculated values of the conventional allowance for 105 deg. total copper temperature and for insulation thickness corresponding to 6600 volts and 13,200 volts. The figures in each table cover a reasonable range in core temperature and in loss ratio (eddy current factors) to fairly represent current design practise.

In Tables V and VI, the values of core temperature and loss ratio are arbitrarily taken so as to cover the range of current design practise. The temperature of the top coil (θ_t) follows from 105 deg. minus 40 deg. air temperature. The temperature drop through the insulation is then 65 deg. minus the core temperature. Knowing this temperature drop, the watts per square inch follows from the thickness of insulation and heat conductivity of the insulation. (This is assumed as 0.003 watts per inch cube per degree). Dividing the watts per square inch of the top coil by the loss ratio gives the watts per square inch of the bottom coil. The constant K and θ_a and the observable temperature rise θ_m can then be calculated and the conventional allowance obviously follows. The measureable temperature rise (θ_m) is calculated from equation (**9**) which is merely a transposed form of equation (**4**):

$$\theta_m = \frac{\theta_t + \theta_i}{2} + \frac{\theta_t - \theta_i}{2\,L\,R} - \theta_a \qquad (9)$$

These calculated values are based on long machines, say sixty inches and longer. A little consideration will show that, for a *given copper temperature,* the conventional allowance is practically the same for all core lengths. Generators, as ordinarily designed have the same current density and ratio of loss to coil surface for a considerable range of core lengths. This results in shorter-core machines having lower copper temperatures and smaller conventional allowances, as a rule, than longer-core machines. But, if machines of short core length were designed with higher current densities and smaller cooling surfaces so as to have the same limiting copper temperature as long-core machines, the conventional allowances would be substantially the same. Therefore, for the purpose of establishing reasonable values of conventional allowance, core length need not be considered.

It will be observed from a comparison of corresponding columns in Tables V and VI that while the watts per square inch for 6600 and 13,200 volts are different, the values of θ_a, θ_m and conventional allowance are identical. In other words, the conventional allowance with given copper temperature, core temperature and loss ratio, is independent of insulation thickness. For purposes of standardization, therefore, no distinction need be made between low-voltage and high-voltage generators, within the range of generator sizes for which the detector method is specified. The reason for this will be evident from equation (**9**). The only term

TABLE VII

CALCULATED CONVENTIONAL ALLOWANCES.

13200-Volt Insulation—125 deg. Copper Temperature.

Insulation Thickness—0.25 inch

Calculations are based on long core machines.

Top coil temp. rise	85	85	85	85	85	85	85	85	85
Core temp. rise	30	40	50	30	40	50	30	40	50
Temp. rise through ins.	55	45	35	55	45	35	55	45	35
Watts per sq. in., top	0.66	0.54	0.42	0.66	0.54	0.42	0.66	0.54	0.42
Loss ratio	1.10	1.10	1.10	1.20	1.20	1.20	1.40	1.40	1.40
Watts per sq. in., bot.	0.60	0.49	0.38	0.55	0.45	0.35	0.47	0.385	0.30
θ_a	9.6	7.9	6.1	8.8	7.2	5.6	7.6	6.1	4.8
θ_m	72.9	75.1	77.2	71.7	74.1	76.5	69.5	72.3	75.2
Conventional allowance	12.1	9.9	7.8	13.3	10.9	8.5	15.5	13.7	9.8

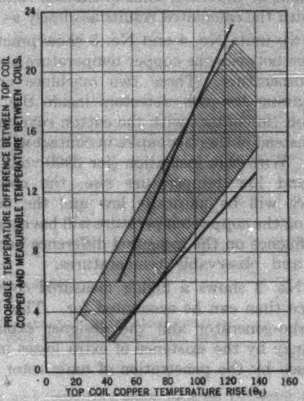

FIG. 10

TABLE VIII.

CALCULATED CONVENTIONAL ALLOWANCES.

13200-Volt Insulation—150 deg. Copper Temperature.

Insulation Thickness—0.25 inch

Calculations are based on long core machines.

Top coil temp. rise (θ_t)	110	110	110	110	110	110	110	110	110
Core temp. rise (θ_i) (assumed)	40	50	60	40	50	60	40	50	60
Temp. drop through insulation	70	60	50	70	60	50	70	60	50
Watts per sq. in. (top coil)	0.84	0.72	0.60	0.84	0.72	0.60	0.84	0.72	0.60
Loss ratios (assumed)	1.10	1.10	1.10	1.20	1.20	1.20	1.40	1.40	1.40
Watts per sq. in. (bot. coil)	0.76	0.64	0.55	0.70	0.60	0.50	0.60	0.51	0.43
θ_a	12.2	10.2	8.9	11.2	9.6	8	9.6	8	6.9
θ_m	94.8	96.8	98.8	92.8	96.4	97.9	90.4	94.0	95.9
Conventional allowance	15.2	14.2	11	17.2	13.6	12.1	19.6	16.0	14.1

in this equation affected by insulation thickness is θ_e. This term, it will be remembered, is

$$\theta_e = K \times \text{watts per sq. in.} \times \text{insulation thickness} \quad (8)$$

But, for constant copper temperature, the product of watts per square inch and insulation thickness is constant, and therefore, θ_e is constant under the assumed conditions.

Tables VII and VIII give similar values of the conventional allowance for higher copper temperatures. Only one value of voltage and insulation thickness is given for reasons just explained.

The results given in these tables give an idea of the probable range in value of the conventional allowance at the limiting copper temperatures for a wide range in values of design factors. These tables could be extended to cover lower and higher core temperatures, and loss ratios, but it is believed that the values chosen are representative of usual design practise, keeping in mind the assumed condition of a fixed copper temperature.

These results are grouped in curve form in Fig. 10. The limits of the cross-hatched area are the maximum and minimum values for each assumed copper temperature rise from Tables VI, VII and VIII. It represents the range of probable values that may be expected in practise.

There have been two propositions advanced as to suitable values of conventional allowance for use in arriving at limiting values of temperature rise for the A. I. E. E. Standards. The first proposition starts with the value of 5 deg. now in the Rules assigning this to Class A insulation temperature limits and doubling this for Class B insulation temperature limits. The second proposition doubles these figures. These two propositions are shown by the heavy lines in Fig. 10. Obviously, the 5 deg.-10 deg. proposition is not adequate to meet the facts, nor is the 10 deg.-20 deg. proposition unduly conservative when it is remembered that the upper limit of values shown in Fig. 10 would be appreciably increased if: (a) allowance were made for increased top coil temperatures caused by the increased eddy current losses in that part of the top coil nearest the air-gap; and (b) if allowance were made for the probability of higher temperatures existing in the individual case than are discovered.

Discussion

For discussion of this paper see p. 529.

Temperature Limits in Large Machines

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Review of the Subject.—*The present Institute standards allow a maximum limit of 105 deg. for fibrous insulation and 125 deg. for mica insulation with an allowance of 150 deg. subject to special guarantees of the manufacturer. In high-voltage machines of large size, the effect of actual copper temperatures higher than 105 deg. may cause softening and disappearance of binding materials, bulging of insulation, and consequent powdering of insulation under periodic pounding of copper on softened material, and ionization at voids so created.*

Operating experience of four large size machines demonstrated the above effects to repeatedly take place in machines operating at copper temperatures of 150 deg. cent. None of these effects were noted in machines operating at copper temperatures of 105 deg. cent. or under. Two machines have safely operated for over three years at maximum copper temperatures of 130 deg. cent. Incorrect conclusions may be made as regards the safe temperature limits by judging the performance of machines unless actual copper temperatures are known. Lower ambient temperatures and fractional loads may reduce the operating temperatures 25 to 35 deg. below the assumed limits.

Machines designed for high temperatures are less efficient than machines designed for cool temperatures, in one instance the difference being as great as several hundred kilowatts at all loads.

The calculation of ventilation of large machines is relatively uncertain; it is of importance to aim at a conservative limit rather than set it too near the danger point.

From the standpoint of economy as well as greater safety, it appears that large machines should not be operated at higher copper temperatures than 105 deg. cent. This means that with outside air ventilation seldom exceeding 20 deg., the maximum standard limit with the standard reference of 40 deg. ambient should be 125 deg. equivalent to 85 deg. maximum rise at the copper. In all cases where the room air is close to 40 deg. the maximum copper rise should be limited to 65 deg.

Other correlated and important features discussed incidentally in the paper are the typical proportionality of life at different temperatures for fibrous insulation, and the new tentative conventional allowance for reducing to maximum copper temperature, readings taken outside the insulation.

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Effect of Temperature and Time. (400 w.)
Effect of Vibration and Mechanical Stresses. (300 w.)
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INTRODUCTION

In response to the request of the Electrical Machinery Committee that I prepare this contribution, I will review the actual temperatures experienced with machines in service and some of the essential features which must be given due weight in the interpretation of such experiences.

The two limits established by the Institute are 105 deg. cent. for fibrous insulation, and 125 deg. cent. or mica insulation, with an allowance of 150 deg. cent. for the latter, subject to special guarantees of the manufacturer. As the established standard ambient temperature is 40 deg. cent., the designer is allowed for his machine a maximum temperature rise at any point on the copper of 65 deg. for fibrous insulation and 85 deg. for mica insulation, with an optional 110 deg. rise, subject to special guarantee.

These are the outstanding and essential bases of A. I. E. E. rating.

In former years, it was the practise to use a double standard of rating, allowing a rise of 50 or 55 deg. for normal loads, and 70 or 75 deg. for overloads, equivalent, for modern machines, to 90 or 95 deg. temperature limit for normal loads and 110 or 115 deg. for overloads.

The writer introduced, fifteen years ago, the method of single rating for turbo-generators which, in the following years, became generally used.[1] In 1914 the Institute adopted the single rating for a larger class of apparatus like motors, transformers, etc., adopting the aforesaid temperature limits for the two classes of insulation.

This was done with the object of simplifying the problem for the manufacturer and the user of apparatus. In substance, the limit of 105 deg. adopted for fibrous insulation was arrived at by striking an approximate average between the two former limits of 90 to 95 deg. for normal loads and 110 to 115 deg. for overloads; the limit of 110 deg. for mica insulation with the optional 150 deg. limit was intended to apply principally to large turbo-generators and large machines.

Considerable objection was raised to the adoption of single rating for commercial motors and in some cases for central station apparatus.

It is not my object here to take any sides in the dispute, which is apparently becoming smoothed out and adjusted.

Note:—(All temperatures given in this paper refer to actual copper temperatures and degrees Centigrade.)

[1] "The standard ratings of Westinghouse alternating turbo-generators are based on two different methods of determining capacity:

First. A rating with gurantees covering performance at normal loads and definite overloads, momentary peak loads being within the guaranteed overload capacity.

Second. A rating corresponding to the maximum safe operating capacity of the particular machine in question, with no guaranteed overload capacity.

This method of maximum rating originated with the New York Edison Company and, though comparatively new, has much in its favor." (The Westinghouse Diary for 1912, page 23.)

Presented at the Annual Convention of the A. I. E. E. Niagara Falls, Ontario, June 26-30, 1922.

It is more important to present a comprehensive survey of the relations, as they now can be ascertained, which have existed in practise between the rated temperature limits and the actual temperatures sustained by the apparatus in service.

Before doing this, it is important to approximately define the relations which different stresses, due to voltage, temperature and time, vibration and mechanical stresses, bear to the life of the insulation.

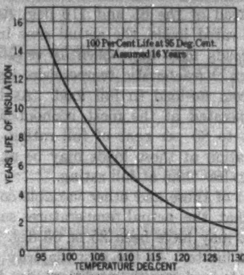

Fig. 1—Life Curve of Fibrous Insulation as Affected by Temperature

Effect of Voltage

It is now a well recognized fact that all insulating materials, including mica, will be destroyed by ionization, if any air voids are present in the insulating covering of an electrical conductor and the potential gradient at these points exceeds the limit of about 75 volts per mill. Imperfections in the material like small iron impurities, will also cause distortions of potential gradients and accentuate the danger of ionization or reduce the effective thickness of insulation. It follows, therefore, that as a general rule the experience with life of insulating materials is only applicable within the limits of voltage of the apparatus investigated.

Effect of Temperature and Time

Up to a few years ago, there was an impression in the minds of operating people that a machine rated for 110 or 115 deg. two- or three-hour overload—would operate safely if the overload was limited to two or three hours *in each day* but would be rapidly destroyed if the overload was carried for much longer periods in one day. The fact that these short overload periods usually covered the occasional peak requirements took away from the operators the inducement to study more closely what higher temperatures would have prevailed if the occasional overloads had been carried for more than two or three hours, and what would have been the effects on the insulation.

In recent years considerable progress has been made in coordinating the relations which exist between temperature, time of application and resultant deterioration and shortening of life. In a paper presented before the Institute in February, 1921, I gave abstracts of results of the classic tests of the British Engineering Standards Committee of 1905, and extended the discussion to experiments made on paper insulation and the observation of considerable investigation of conditions of paper insulation used in cables subjected to occasional high temperatures. At the same meeting D. W. Roper presented results of similar observations, while Fisher and Atkinson gave an experimental formula for determining the reduction of life strength of paper subjected to different temperatures. From these and other studies made on fibrous insulation, it is possible now to plot a characteristic curve of the effect of temperature upon the life of fibrous insulation if not otherwise affected by ionization or mechanical stresses. While the actual years of life at different temperatures are not established by experience, the relative proportionality of the length of life may safely be represented by the relation given by the curve in Fig. 1. This tentative curve would roughly indicate that, other things being equal, a machine operating at 105 deg. will have a life of 50 per cent of a similar machine operating at 95 deg. Similarly, if we operate a machine 90 per cent of the time at 95 deg. and the remaining 10 per cent of the time at 115 deg., the life of the machine will be 77 per cent of the virtual life at 95 deg. for 100 per cent of the time. From this law we can now more clearly see how the double rating may have practical advantages.

From similar studies on mica insulation, there appears to be no doubt that aside from the influence of ionization due to voltage and mechanical stresses, mica insulation can safely withstand almost indefinitely high temperatures probably as high as 200 deg.

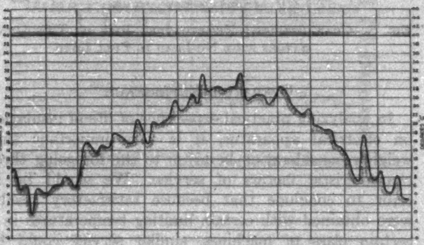

Fig. 2—Five-Day Average of Maximum Air Temperatures in New York City for the Year 1921

Effect of Vibration and Mechanical Stresses

Vibrations are obviously always present in rotating machinery due to movement and reactions of the rotating elements and the periodic pounding of the insulation due to the drag of the rotating field and the abnormal heavy blows under system short circuits, etc. With well wrapped and unimpaired insulation and well supported coils, these stresses will not affect the elastic limits of the materials, but if the copper temperature is high, the varnishing materials in the insulation may distill and loosen the binder, allowing a play for the copper to pound and powder the insulation as a continuous drop of water will hollow out a stone. Stresses in the insulation are also imposed by different rate of expansion and contraction of the copper and the insulation under large changes of temperatures which may cause bulging and voids in the insulation between the insulating slots, with consequent ionization if the voltage stresses are sufficiently high.

The possible damages to insulation due to vibrations and mechanical stresses are, therefore, to be looked for mainly in machines of large power and relatively high voltages where ionization may ensue. From the coexistence, in large power machines, of high temperatures with high voltages, failure may be caused either by bulging of insulation due to uneven expansion and contraction, or powdering of insulation due to softening and disappearance of the varnishing materials.

Where only low pressures of around 110 volts are present, relatively high temperatures like 110 deg. for fibrous insulation do not appear to destroy the usefulness of the insulation. Where voltages are high, the mechanical stresses must be seriously considered for temperatures higher than 105 deg. for all types of insulation.

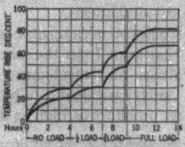

FIG. 3—CHARACTERISTIC TEMPERATURE RISE OF TWO GENERATORS FROM NO-LOAD TO FULL LOAD

OPERATING EXPERIENCE

In analyzing practical experience of life of insulation on electrical apparatus, it is very important that weighty consideration be given to the foregoing three characteristic factors of service. We would be in error to conclude that because satisfactory results were obtained with certain limiting temperatures in a certain class of machines, similar service could be obtained in other classes of machines.

One of the greatest difficulties in making comparisons of practical experience with apparatus in different installations is the uncertainty of the actual temperatures which have actually prevailed in the machine.

The most common error made by engineers discussing temperature limits is to assume that a machine rated for say 105 deg. if insulated with fibrous materials, or 150 deg. if insulated with mica, because it has operated successfully for a number of years, therefor 105 deg. or 150 deg. have proved satisfactory in practical service. Nothing can be further from the truth than such assumptions.

The machine may be cooled by air usually 10 to 20 deg. lower than the 40 deg. standard ambient. Fig. 2 gives the five-day averages of maximum daily air temperature for 1921 in New York City. These show, at a glance, the large margin between the actual maximum temperature throughout the year and the assumed 40 deg. base of reference.

The machine may never have carried the rated load, so that instead of the 65 and 110 deg. rises allowed for the full rated loads, the actual rises in operation at partial loads may have been 10 or 15 deg. less. Fig. 3 shows characteristic temperature rises for two machines from no-load to full load. As large turbo units are operated at the most economical point at 75 per cent to 80 per cent of full rating, the actual rise in operation at those loads may be at least from 10 to 15 deg. less than at full rating.

The result of these and other variable conditions of service is that the actual temperatures sustained by the machine may have been 25 or 35 deg. lower than the assumed limits. As the vast majority of the machines operate under such conditions, it becomes of vital importance that when we speak of temperature limits, we clearly state whether we mean the actual temperature or an arbitrary figure assumed for purposes of commercial ratings and arrived at by striking a reasonably safe limit, which, on account of the aforesaid service conditions, it is not expected to be reached in practise by the vast majority of the machines. If in applying the results of our experience we will eliminate from consideration all machines which, while nominally rated at say 105 deg. or 150 deg., in practise have only operated at 20 or 30 deg. below those limits, we will come to consider only relatively few cases where actual temperatures of 105 or 150 deg. have really obtained.

Only from the experience of such machines can we derive conclusions as to safe temperature limits.

The maximum copper temperatures of the machines in the following illustrations were obtained either by direct copper temperature measurements or by adding to the highest reading of the thermometer detectors between coils an allowance calculated on the basis of 2½ per cent of that rise over the inlet air for each thousand volts of the rated voltage of the machine. This correction seems to be as close as we can ascertain from elaborate tests which are under way under the auspices of manufacturers and large users.

In interpreting these records, it must be remembered that these maximum temperatures were present only during the period of peak load less than four hours a day, and generally of much shorter duration. For the balance of the time, the copper temperatures were lower than the indicated maximum, mainly on account of lower loads and sometimes on account of lower temperature of the inlet air.

Fig. 4 gives the log of maximum temperatures sustained by one turbo-generator, which has had several failures, and Fig. 5 the log of maximum temperatures representative of three turbo generators, two of which have had several failures. The characteristic features of these failures were either bulging insulation, powdering of filler and mica at edges of copper windings or overheating of iron laminations.

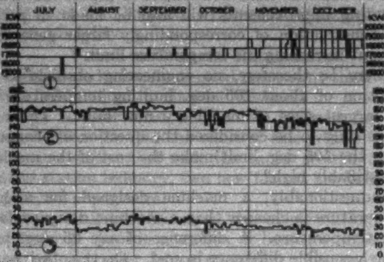

Fig. 4—Characteristic Operating Conditions

21,000-kv-a., 1500-rev. per min., 11,000-volt generator
(1) Daily maximum kw. load
(2) Daily maximum copper temperature
(3) Inlet air temperature
For failures, see curve of machine *A* in Fig. 6.

The records of coil burn-outs of the three machines which had failures are graphically plotted in Fig. 6 in reference to total hours of service between failures. The third machine of the same type as *B* and *C* operated under the same conditions of service without failures, though when the coils were removed they showed the same characteristic features of impaired insulation.

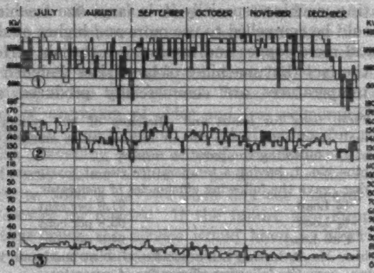

Fig. 5—Characteristic Operating Conditions

For three 19,000-kv-a., 1800 rev. per min., 8000-volt generators
(1) Daily maximum kw. load
(2) Daily maximum copper temperature
(3) Inlet air temperature
For failures of two units, see Curves of machines *B* and *C* in Fig. 6

The records of failures of machines designed for high temperatures could be extended, but the writer was not able, within the very short limits of time allowed for the preparation of this paper, to secure the necessary details of operating temperatures and hours of service to make the presentation complete as in the case of the three machines *A*, *B* and *C*.

In Fig. 7 are given the maximum copper temperatures representative of five machines, one of which has operated for eight years, two for over two years and two for five months, without failures.

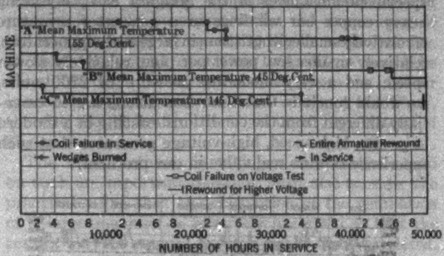

Fig. 6—Record of Generator Coil Failures

Machine *A*—21,000-kv-a., 1500-rev. per min., 11,000 volts
Machines *B* and *C*—19,000 kv-a., 1800-rev. per min., 8000 volts
Refer to Figs. 4 and 5 for operating conditions

In Fig. 8 are given the maximum copper temperatures representative of two machines which have operated from three to four years without failures.

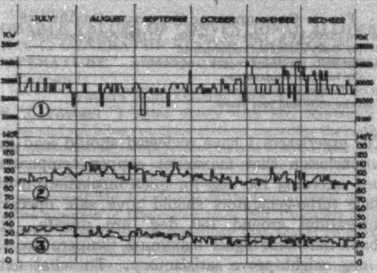

Fig. 7—Characteristic Operating Conditions

For four 35,000-kv-a., 1500-rev. per min., 11,000-volt generators
one 30,000-kv-a., 1500-rev. per min., 11,000-volt generator
(1) Daily maximum kw. load
(2) Daily maximum copper temperature
(3) Inlet air temperature
No coil failures have occurred on these machines.
One in service for eight years, two for two years, and two for five months.

These data cover varied experiences with large machines of different manufacturers.

Deductions From Experience

From this experience it appears that we would be justified in concluding that mica insulation would not safely withstand temperatures of 150 deg. in high-voltage turbo-generators. This conclusion would seem to be in disagreement with the often repeated statement that mica insulation on the original Niagara generators safely withstood temperatures as high as 185 deg. for a long period of years. If, however, we apply to that experience the consideration of the three factors with which I prefaced this presentation, and recollect the special circumstances of the Niagara case, involving heavy copper bar windings in a generator armature of relatively smaller length than in large turbo-generators, relatively smaller kw. power per pole, relatively slower speed, and a very moderate pressure of 2200 volts, we would conclude that these conditions are so essentially different from the conditions existing in a modern large size, high-speed, high-voltage generator that such experience is of no real value in our problem.

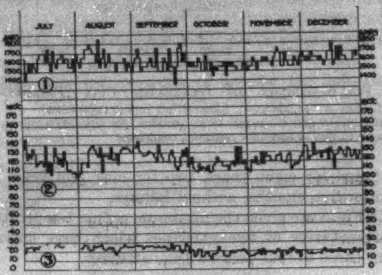

FIG. 8—CHARACTERISTIC OPERATING CONDITIONS

For two 35,000-kv-a., 1200-rev. per min., 12,000-volt generators
(1) Daily maximum amperes load
(2) Daily maximum copper temperature
(3) Inlet air temperature
No coil failures have occurred on these machines.
In service three and four years.

The experiences I have reviewed should lead us to the conclusion that maximum copper temperatures of not exceeding 105 deg. for mica insulation in high-voltage turbo-generators should give safe operation. Temperatures around 150 deg. are unsafe. It is probable that some higher maximum temperature than 105 deg. might prove satisfactory. To what extent the limit of 105 deg. might be safely raised is a question which cannot be definitely settled in the light of the experience available.

ENGINEERING AND ECONOMICAL CONSIDERATIONS

Having arrived at the conclusion that, with the present knowledge, about 105 deg. should be the limiting copper temperature in large machines, the question arises whether it is practical and economical to impose such a limit on the industry.

From an engineering standpoint, there appears to be no difficulty in building 105 deg. generators larger than required for the largest size steam turbines that have been produced for the two speeds of 1200 and 1500 revolutions. For the 1800- and 3600- rev. per min. speeds, the 105 deg. generators are today close to the limits of the steam turbines, *i. e.*, about 8000 kv-a. and 35,000 kv-a. at 85 per cent power factor for 6000-kw. and 30,000-kw. steam turbines. If improvements in the steam turbine will make it feasible to increase the capacity of the 3600- and 1800-revolution turbines, it seems reasonable to expect that corresponding improvements will also be made to permit the construction of correspondingly larger generators without increasing the temperature limit.

There is, therefore, no engineering obstacle to the adoption of about 105 deg. limiting temperature for the largest sizes of machinery now built. There remains only to be considered the question of economy. Does the 105 deg. limit make the cost of the machine unjustifiably high?

Unquestionably, a machine designed for a high temperature is cheaper than a machine designed for a cool temperature. A difference of say 25 deg. may make a sensible difference in cost. On the other hand, the machine designed for a cool temperature will be more efficient than the machine designed for a high temperature. It is difficult to evaluate in dollars per kilowatt to what extent these differences will affect the net results.

For an approximation, I would make a rough guess that the purchaser would be justified in paying $1 per kilowatt more for the cooler machine for the saving in higher efficiency.[2] This would leave the purchaser the net advantages of the greater factor of safety of the machine designed for cool operation.

As to the manufacturer, I cannot state how far the $1 would go to cover the increased cost of the cool operating machine especially if, in large size machines, he should be compelled to use more and higher quality iron and more copper and insulating materials. However, the fact that machines of large sizes designed for cool temperatures are commercially produced and

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[2] From tests for losses and efficiency of two generators under load conditions, using the air measurement method, are obtained the following comparative results:

Machine No. 1, having a temperature rise at maximum load of 120 deg., gave the following efficiencies of generator:

½ Load	91.9 per cent
¾ Load	93.8 per cent
Full Load	94.9 per cent

Machine No. 2, having a temperature rise at maximum load of 80 deg., gave the following efficiencies of generator:

½ Load	94.6 per cent
¾ Load	96.1 per cent
Full Load	96.8 per cent

The total losses of machine No. 1 exceed those of machine No. 2, as follows:

½ Load	331 kw.
¾ Load	389 kw.
Full Load	405 kw.

Even allowing for inaccuracies in the method of measurement, the results illustrate the point that, at least in this case, the cool machine had a materially higher efficiency than the hot machine. While with other machines the differences may not be as great, they will undoubtedly be of sufficient value to produce a sensible saving at the coal pile in the operation of the cool machine.

marketed would seem to indicate that the 105 deg. limit does not impose unjustifiably high costs of manufacture.

The result of these considerations is that while nominally the machine designed for cool temperature is somewhat more expensive to build than a machine designed for high temperature, its slightly increased cost is more than balanced by its greater efficiency and greater reliability.

VALUE OF GREATER RELIABILITY

There is undoubtedly general agreement that, other things being equal, a machine designed for cool temperature is safer than a machine designed for high temperature. To find the value of this greater safety we must consider that with the rapid growth of the central station industry, two new factors are becoming of primary importance.

One is, that with increased size of generating units and fewer of them in a station, it becomes imperative to obtain a greater factor of safety. Also, with the expansion of the systems and superpower line interconnections over large areas, the load factors on the generating plants tend to increase, requiring longer service from each generating unit.

The other is that, with the development of new plants improvements always become available in the art, like utilization of higher steam pressures, higher superheat, higher boiler economy, less heat losses in gases, better economy of auxiliaries and better heat balance. To secure the economy of this better efficiency, new generating units in old as well as new stations must be operated to carry the base loads of the system while the older units are operated to carry the balance of the loads of shorter duration. Therefore, the burnout of an armature in a modern generator is vitally serious, not so much for the damage and cost of repairs, but mainly for the loss of business, if it cripples the system, at the time of peak loads, and the increased cost of operation of older and less economical units while the large new unit is out of service for repairs. With prevailing prices of coal, the failure of a large unit may cause a loss in production costs alone of $500 to $600 a day for each day the machine is out of service for repairs. If the failure also happens at a time when the service would have to be crippled, the losses would be incalculably serious.

CONCLUSIONS

Central station managers are keenly alive to the necessity of securing the most reliable apparatus to safeguard their interests and the interests of the public they serve. Designers must approach the problem of producing machines of highest reliability. Central station engineers should cooperate with the manufacturers in standardizing for all bidders the same limit of temperature so as to place the competitive business on equal terms. The present Institute rule which specifies 85 deg. copper rise for mica insulation but also allows 110 deg. cent. subject to special guarantees is not right. Only one standard should be adopted for the best interests of all concerned. The limiting copper rise of 85 deg., which corresponds to the present *conventional* limiting temperature of 125 deg. for the *conventional* 40 deg. standard ambient temperature, appears to be the maximum safe limit dictated both by reasons of economy and safety. With this conventional limit of 125 deg. it should be understood that in practise it would be expected that the temperature of the inlet air would be around 20 deg. instead of 40 deg. so that the actual operating temperature would be about 105 deg. In all special cases where the inlet air is near 40 deg., as with machines in Fig. 4 and Fig. 7, the rise should be limited to about 65 deg. instead of 85 deg.

The manufacturer, in taking a conservative stand on such an important question, must also consider the practical point that the calculation of the ventilation of a large machine is relatively uncertain so that the results may be several degrees higher than calculated. It becomes, then, of practical importance to aim at a lower limit to permit of some higher variations to which the user may adjust himself without requiring expensive changes, rather than to set the limit too near the danger point so that any higher deviation would necessitate derating the machine or subjecting it to early failures.

Discussion

QUESTIONS RELATING TO STANDARDS OF RATING (Newury);

PROBABLE VALUES OF CONVENTIONAL ALLOWANCE FOR A-C. GENERATOR STATOR WINDINGS (Newbury)

TEMPERATURE LIMITS IN LARGE MACHINES (Torchio);

Niagara Falls, Ontario, June 28, 1922

W. J. Foster: I agree closely with Mr. Newbury's conclusions and with his recommendations regarding the method of rating machines by temperature rise and also the figure that he has mentioned as the ultimate temperature rise of Class *B* insulation in the armature windings.

This paper of Mr. Newbury's on the Conventional Allowance is a fine example of laboratory work, but I consider it like all laboratory investigations, something that should be used with caution in applying the results.

There are differences in the way in which the temperature is attained in the different parts of the Laboratory Model that vary very widely from what exists in rotating electric machines. For example the temperatures of the iron are obtained by heat entirely from within the coils embedded in the slots, while in the ordinary machine, only about one-half of the heat is generated in the coils.

Now, in the case of the heat originating inside of the insulated coils, it is necessary to have the temperature attain a very much higher value in order to bring the core up to the temperatures that are carried through the investigation as shown in the tables ranging from something like 10 deg. to 70 deg., and consequently the embedded detector which lies in the line of the heat dissipation has quite a different temperature; in other words, the difference between the inside temperature of the coil and the embedded detector is in my opinion, greater than in the average rotating electric machine. Similarly, the variations that are taken to represent the different types of machine—long core, short core and the different potentials, I do not think should be taken as equivalent to test results on actual machines.

I speak of this, because I do not want it to be generally imagined or thought there will be a 15-deg. difference, between the measured temperature and what may exist inside.

In these investigations, concerning which I have a great deal of interest, having more or less charge of such investigations in our company, fully one-half of the machines referred to in Mr. Newbury's paper, the inside temperatures at the ratings of the machines, in many cases were no higher than those measured by the detector, indicating no drop whatever, which is not unreasonable. The fact is, we can conceive of a machine so designed that the temperatures in the inside of the insulated coils are no higher than at the spot where embedded detector is located outside the insulated coil.

Such machine would involve a broad slot, and thin insulation, and a very narrow temperature detector, and the machine very conservatively rated, with certain relations existing between the heat generated in the iron and that in the copper.

I was very much pleased with Mr. Torchio's paper, since it is a contribution along the lines that are very greatly needed. It is experience that should be taken as the basis of standardization. In my opinion, standardization should not anticipate too much the possible progress that may be made. We should know our ground well, before we standardize for the future. Standardization is largely a matter of present knowledge, based on past experience.

As I understand Mr. Torchio and Mr. Newbury, the 80 deg. allowable temperature rise is recommended, and I am in sympathy with basing the rating on temperature rise, rather than hot spot temperatures. As I understand it, this 80 deg. rise is to be considered good practise, but the upper limit of good practise.

R. F. Schuchardt: The great importance that attaches to this subject is due not only to the millions of dollars invested in these large units, but also to the fact that the reliability of the service, and also in large measure the safety of the system, are involved.

Mr. Torchio deserves the gratitude of the industry for the most heroic insistence and persistence with which he has fought for conservatism in this line, and I want to voice my accord with his position. As a result of his work this compromise of 80 deg. has been reached. From the very limited data that are available, this must of necessity be a compromise.

On the one hand, the maker naturally is optimistic over his own work, and perhaps he has more faith in the materials than the user would have, and feels that a higher temperature makes for greater progress. It is entirely natural he should feel that way. The engineer, who has these large systems to operate, on the other hand, believes that reliability is the first thing to be sought, and the very last thing to be given up. Because of their comparatively high economy, these large units must be as dependable as it is possible to make them. The economy is realized only when these units are in condition to be operated on the base load. The operating engineer, therefore, naturally does not take the same optimistic view of the situation as the manufacturer might. He must be conservative.

We have heard that some of our foreign colleagues feel that higher temperatures are advisable. Without data, that seems to us as accepting a shorter life, and particularly for the very large units with the long coils. It is not entirely a question of the temperature that the materials themselves will withstand, so much as the mechanical result of the expansion and contraction, due to these large ranges in temperatures.

I think the evidence of the failures in Mr. Torchio's machines indicate it is not the temperature itself that caused the breakdown, so much as the effect of expansion and contraction—the mechanical rubbing on the mica, and grinding it up.

In conclusion, the thing we should do first is to cooperate to get more data, but meanwhile the user, because of his responsibility for safety and for reliable service must be conservative.

W. F. Dawson: I think, with the gentleman who spoke before, that we are to be congratulated on this compromise, as we call it, because I know there are some members of the Institute who think the value is too low, and others who think it is too high. I personally think that they have decided on a splendid value for the rating of Class B insulation in stators.

There is one feature about the temperature of 100 deg. cent., which I do not think has been mentioned, although it may have been hinted at. Nothing has been said about the possibility of aging of armature steels at high temperatures. I have not had any personal experience with aging, but I do know from the experience of transformer designers that steels which are not alloyed, which are not the silicon steels, will not stand continuous operation at 150 deg. cent., without a large increase in the loss.

As I understand it, this happy compromise allows 80 deg. rise with the ambient temperature of not over 40 deg. That makes 120 deg., and when one adds the hot spot correction, of, say, 10 deg., gives total of 130 deg. That is high enough, but I believe it is not too high.

I think that Mr. Newbury recommends 100 deg. rise in field. That seems reasonable and I don't think we need go down to 80 deg. rise.

You can say that you want something reliable to be able to understand what the manufacturers are bidding on—yes, but you want something which is competitive too, to get the most in capacity, for the dollars you put into your investment. We do not want to fix any false standards we cannot live up to.

R. B. Williamson: I feel very much gratified to see that we are going back to the idea of specifying a straight temperature rise. Machines have been built for a great many years under a specification of 40 deg. cent. rise by thermometer for Class *A* insulation.

Now, in the case of Class *B* insulation on stators, we are considering 80 deg. rise, with the difference that instead of specifying it by thermometer we are specifying it by imbedded detector and omitting all temperature corrections. This simplifies the whole method of determining temperatures, and it is in effect simply going back to the former method except that the measurement is made in a different way.

Mr. Schuchardt has brought up an important point in connection with Mr. Torchio's paper. That is, it is not, whether 80 deg. or 90 deg. is safe for mica, because we know that mica in itself will stand higher temperatures than these, but it is a question as to the mechanical effects of the high temperature on insulation. It has been demonstrated by Mr. Torchio that high temperatures may affect the binder causing the insulation, in some cases to loosen to a certain extent; we then have the condition of loose conductors in a magnetic field, and these are bound to vibrate more or less and chafe the insulation, so that a breakdown finally results from the mechanical action rather than from the heat. In rotors, the insulation will stand these high temperatures without trouble, because the mica is held very firmly mechanically, and there is not the opportunity for vibration that exists in the stator. Also in the rotor the voltage is low whereas in the stator of large machines the voltage is usually high.

C. E. Skinner: Referring in Mr. Torchio's paper to Figs. 4, 5 and 8, the graphs showing the temperatures of these machines. Mr. Torchio states that the temperatures are either from copper measurements or are arrived at by a method giving the equivalent conventional allowance. Now, these particular machines 4 and 5, are older machines, and they have heavy, solid conductors, while the machine referred to in Fig. 8 has laminated conductors. It is very possible, therefore, that the differences in Figs. 4 and 5, as against Fig. 8 are greater than the figures given in Mr. Torchio's graph, for the reason that the eddy currents, particularly in the top conductor, are probably very much greater in the first two machines than in the later machines, and consequently the earlier machines have a greater hot spot temperature than the graph would indicate.

I think that may possibly account for the greater difficulty of the earlier machines.

F. W. Peek, Jr.: I do not believe that it is good engineering to use insulations at extreme temperatures. It is my opinion that the Sub-Committee has come to a fortunate conclusion in adopting this principle.

H. L. Wallau: In connection with Mr. Torchio's paper, there have been a certain number of experiences in Cleveland which may be of interest. The question raised by Mr. Torchio as to what limiting temperature shall be standardized for large turbo-generators is of vital importance to the central station industry, and requires thorough and painstaking investigation.

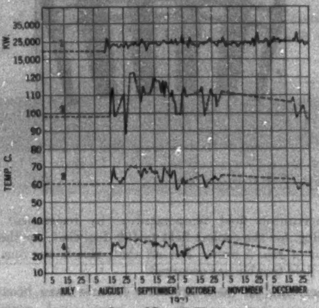

FIG. 1—OPERATING LOG NO. 8 TURBO-GENERATOR, LAKE SHORE STATION FOR 5 MONTHS OF 1921, 25,000 KW., 11,431 VOLTS, 1800 REV. PER MIN.

1. Daily Maximum Kw. Output
2. Daily Maximum Field Temperature
3. Daily Maximum Armature Coil Temperature
4. Daily Temperature of Intake to Air Washer-Field temperatures calculated from rotor resistance.

Dotted lines indicate no recorded readings.

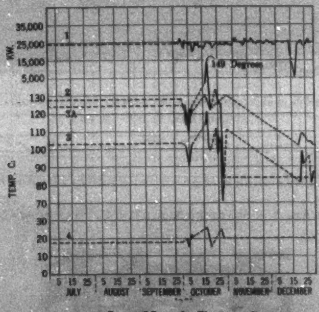

FIG. 2—OPERATING LOG NO. 9 TURBO-GENERATOR, LAKE SHORE STATION FOR 3 MONTHS OF 1921, 25,000 KW., 11,430 VOLTS, 1800 REV. PER MIN.

1. Daily Maximum Kw. Output
2. Daily Maximum Field Temperature
3. Daily Maximum Armature Coil Temperature

3A. Daily Maximum Calculated Temperature on 2¼ Per Cent Increase per 1000 Volts

4. Daily Temperature of Intake to Air Washer

Dotted lines indicate no recorded readings.

Mr. Torchio's curve, Fig. 1, showing the life curve of fibrous insulation based on the data obtained by three independent sets of investigators is very interesting, but is limited to the effect of temperature alone and cannot of course, show the combined effects of temperature, mechanical stress and ionization.

It is possible that the shape of this curve holds true for Class *B* insulation although by definition the "binder is used for structural purposes only, and may be destroyed without impairing the insulation or mechanical qualities of the insulation."

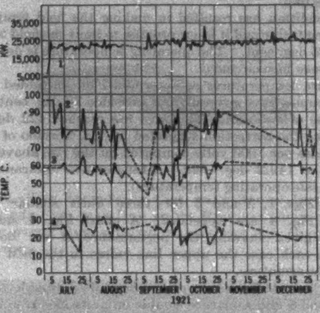

FIG. 3—OPERATING LOG NO. 10 TURBO-GENERATOR, LAKE SHORE STATION FOR 6 MONTHS OF 1921, 25,000 KW., 11,431 VOLTS, 1800 REV. PER MIN.

1. Maximum Daily Kw. Output
2. Maximum Daily Field Temperatures
3. Maximum Daily Copper Temperatures
4. Maximum Daily Temperature of Intake to Air Washer

Dotted lines indicate no recorded readings.

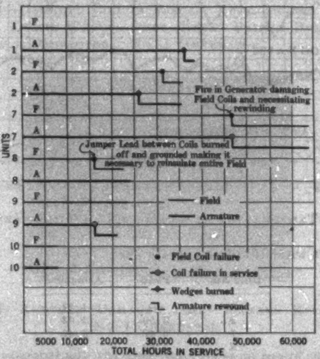

FIG. 4—RECORD OF GENERATOR COIL FAILURES

Hours out of service for rewinding armature and field are deducted from these given hours.

If this is strictly true the life curve for Class *B* insulation as affected by temperature alone, probably would be quite flat over a range of 150 deg. cent. in temperature.

Fig. 2 shows that the average air temperature in New York is much nearer 20 deg. than 40 deg. cent. with a maximum for the year of 32 deg. cent.

This is roughly typical of our lake cities, but is probably much lower than temperatures prevailing in the Mississippi Valley during the summer months.

It would therefore seem that the standard ambient reference temperature of 40 deg. cent. should be retained.

Mr. Torchio's Figs. 4, 5 and 6 indicate conditions prevailing in his plant quite at variance with those obtaining in Cleveland. In general, no machines in Cleveland have been operated at armature temperatures of 145 deg. to 155 deg. cent. maximum.

The bulk of the Cleveland load is an alternating-current industrial supply, the power factor averaging about 80 per cent during the day.

This condition has resulted in making the field temperature the limiting factor and it is our practise to limit the field temperature to 125 deg. cent. The operating temperature is determined by resistance measurement.

Armature temperatures as determined by imbedded coils or thermo-couples have generally not exceeded 70 deg. cent. except in the case of one unit. This unit has reached 122 deg. cent. and making the correction suggested by Mr. Torchio of 2½ per cent increase per 1000 volts computed on the rise above air has reached the 149.2 deg. cent. (Manufacturer guarantees 150 deg. cent. safe operating temperature).

Charts Figs. 1, 2 and 3 for three units similar to Mr. Torchio's Fig. 4 are appended. A chart Fig. 4 similar to Fig. 6 is given showing the performance of our horizontal units. In each case the upper line refers to the field and the lower to the armature.

It will be noted that we experienced field trouble on units No. 2, 7 and 8 and armature trouble on units No. 1, 2, 7 and 9.

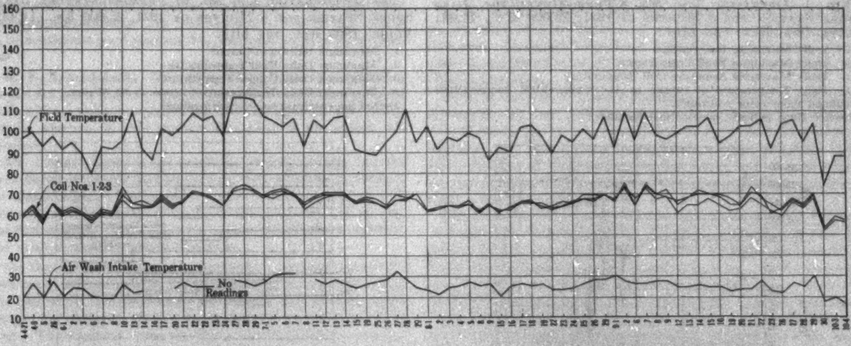

FIG. 5—TEMPERATURE READINGS ON NO. 1 TURBO-GENERATOR LAKE SHORE STATION STARTING APRIL 4, 1921 TO OCTOBER 31, 1921

The life without failure in years was

Unit No.	Field	Armature
1	—	4.17
2	3.59	3.03
7	5.42	5.42
8	1.82	—
9	—	1.82
10	—	—

(Dashes indicate no failure to date.)

The record of our vertical 14,000 and 15,000 kv-a., 1 power factor, 11,430-volt units is as follows:

Unit	Installed	Repairs	Date	Elapsed time
No. 3	Sept. 1911	Field reinsulated	July 1920	8.8 yrs.
" 4	Aug. 1911	" "	May 1918	6.7 "
" 5	Dec. 1912	No repairs		9.5 "
" 6	Oct. 1913	Grounded field repaired	May 1918	4.6 "

All of these units are in commission.

The maximum armature temperature (by thermometer) reached by any unit was 69 deg. cent., and the approximate average armature temperatures during the summer months have been 55, 58, 50 and 50 deg. cent. respectively since installation.

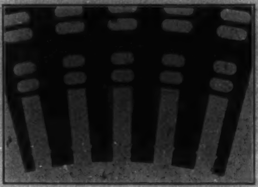

FIG. 6—ARMATURE LAMINATION SHOWING PORTIONS SUBJECTED TO HIGH TEMPERATURES WHICH DESTROYED INSULATING VARNISH NO. 9 GENERATOR

The maximum field temperatures (by resistance) reached were 93 deg. for the coolest field to 109 deg. cent. for the hottest field, that of No. 5 unit. For all that, this is the one unit on which no field trouble has occurred.

In practically all cases armature failures have been accompanied by more or less pulverization of the mica, indicative of mechanical pounding, often by bulges in the insulation, resulting in air pockets and consequent ionization.

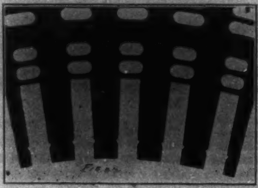

FIG. 7—ANOTHER PORTION OF OVERHEATED ARMATURE CORE NO. 9 GENERATOR

The armature failures of two of our horizontal units were plainly the result of grounding of the corona shields in certain slots. On rewinding these shields were omitted.

In the case of a third unit, this was suspected but could not be definitely established.

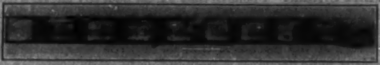

Fig. 8—A Portion of a Damaged Coil that Crossed Ten Air Ducts. Coil Bulged and Insulation Cracked at Edge of Ducts. No. 9 Generator.

Fig. 9—Close Up of Fig. 3—Showing Bulges and Powdered Mica Insulation and Effect of Static. No. 9 Generator.

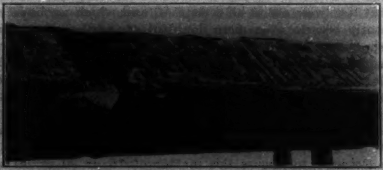

Fig. 10—Close Up of Other Side of Bulge No. 3 Shown in Fig. 4—No. 9 Generator

Fig. 11—Close Up of Another Bulge in a Damaged Coil. No. 9 Generator

The fourth unit which failed ran hotter than the others from the beginning. In installing the armature coils it seems that the slots were filed to allow the windings to be inserted. It is our belief that the burrs resulting from this filing, caused severe local heating in the laminations. In the accompanying cuts, Figs. 6 to 12, the lightly shaded areas show the spots where the insulating varnish on the laminations had been completely destroyed.

It was necessary to install an entire set of new laminations as well as a complete armature winding.

Two other illustrations Figs. 13 and 14 show the condition of various coils of No. 1 generator, in one a burned wedge shows very plainly. The bulges and powdered mica (white pots on coils) are readily discernible.

After this machine unit No. 9 had been rewound and placed in service one of the detectors indicated a coil temperature of 195 deg. cent. The field was withdrawn and the armature examined. A small hexagonal nut was discovered lying on top of one of the slots near the detector in question. When in operation the magnetic stresses had caused this nut to vibrate and peen the edges of the laminations considerably. This confirmed our belief that the original trouble was caused by the filing of the armature slots. (In the rewinding process the slots were lined up and after the coils had been inserted the bolt holes were filed where necessary for the proper insertion of the through bolts.)

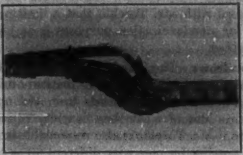

Fig. 12—The Section of Coil that Broke Down. The Bend in the Coil was Due to its Removal from the Slot. Note that the Break-Down was at the Air Duct. No. 9 Generator.

Fig. 13—Damaged Coil in Place. Note Burned Wedge at Left. Other Wedges were Either Partly Burned or Completely Destroyed. No. 1 Generator.

Fig. 14—Another Damaged Coil—Wedges Removed. No. 1 Generator

After the nut was removed and the edges of the laminations ground and varnished, insofar as possible, the machine was again put in service.

Before carrying load, but operating at full speed and excitation, it was found that five of the detectors indicated an average temperature of about 78 deg. cent. while the sixth, still showed high, reaching 131 deg. after a 3½ hour run. Intake air 17 deg., exhaust air 29 deg., maximum rise 114 deg. cent.

Under load this difference in temperature between different detector coils irons itself out and the maximum difference noted is about one-third as great as that and often less.

In conclusion, our experience as a whole indicates that our troubles have not been caused so much by temperature as by mechanical pounding and ionization.

Since the higher temperatures would aggravate these effects, we are in accord with Mr. Torchio that a limiting temperature of 125 deg., for standardization purposes is as high a value as should be adopted.

H. R. Woodrow: The manufacturers are greatly indebted to Mr. Torchio for bringing before the Institute in such concrete form the requirements and methods from the operating field, giving a definite idea of what they consider reliable and satisfactory service. Mr. Torchio is also responsible to a large extent for making it possible for men with different ideas to get together on temperature ratings. For instance, on conventional allowances opinions vary from 5 to 30 deg. In the larger machines of today, we know from experimental data what these allowances should be.

Another point which the Institute should clear up is the classification of Class *B* insulation. As Mr. Newbury brought out, there is still considerable uncertainty as to Class *B* insulation, and how much Class *A* material should be permitted in its construction.

The question of field insulation temperature limits as Mr. Williamson brought out should be definitely classified. There has been some trouble due to field insulation failures, and as the papers do not cover that point, would it not be possible to have it covered in this discussion.

H. G. Reist: I too wish to congratulate the Committee on getting back to the old standard of giving the rise instead of the more complicated expression for determining the temperature, which we have used for the last several years. It has been pointed out that since the French standard has been changed, and the American standard of a lower temperature has been adopted, that they have had better results than formerly with their machines.

A friend of mine, an engineer, who has been in France within the year, told me that in one installation of large American built induction motors that was made during the war, the owners expressed extreme delight in the service which they had obtained. They said they never had an experience such as they had with the use of these motors, because they have not had any trouble from burnouts. That is due to the fact that they were running at lower temperatures than the French motors.

Several speakers have expressed the opinion that 80 deg. rise for Class *B* insulation, which we all know usually has some organic material in its makeup, should be the limit.

I would like to ask the question, since the French engineers have followed our lead with good results, and we would like, as far as possible to lead the rest of the world in this industry, is it good policy for us to standarize to the limit?

This idea I am going to speak of has already been expressed in a different way, but it seems to me the question may be resolved into a mathematical equation, the same as the amount of material you can afford to put in a machine, or how much you can spend for the roof on your house,—Is it not a question whether the first cost, the cost of the loss in the machine, the repairs, and the lack of service of one temperature balance against similar results if you use some other temperature. Would not the solving of that equation give you the answer? It has been pointed out that generally high temperatures means greater loss and less efficiency, and we all agree that however good we make an insulation, for 80 deg. or any other temperature rise, it will be a little bit longer lived if we run at lower temperatures and therefore repairs will be less frequent and the expense of repairs and the loss from lack of service will be less.

James Lyman: I believe that we all heartily agree with the standardization that has been presented to us. The manufacturers of large turbo-generators have so improved and advanced the design of the machines, that as regards temperature they are able to build machines corresponding to these lower temperatures.

There is no part in the development of the industry of greater importance than the reliability of these big turbo-generators. We have read, within a few months, the report of the Super-Power Committee. More rapidly than most of us realize there will be in use throughout the length and breadth of this country, a universal 60-cycle power supply. It will be on the order of the outlines of the Super-Power Committee. On the Pacific Coast, in the Middle States, in the East, we shall soon have in operation 220-kv. power lines, transmitting power of the order of 100,000-kilowatts per circuit supplying cheap power, not only in our industrial centers but wherever industry wishes to locate in the country, and nothing can be of more vital importance to the success of these undertakings than the reliability of the large turbo-generator units which are the source of supply for these systems.

L. T. Robinson: It seems to me we have made a great gain in our method of procedure, by giving weight to the things which we know about, as opposed to starting from the end that we were least certain of, to arrive at the result. On the old plan we started with 125 or 150 deg., or whatever it was, and which we at that time were not at all certain of, and which we have subsequently become even more doubtful of, and we assumed a certain conventional allowance, and took that off, then we assumed an ambient temperature of the surrounding cooling medium, and took that off, choosing such values so that after we had taken them off, we would have the circuit temperature rise left.

Now, we have decided to start from the other end, and take what we know, and forget the other things. Therefore, it is unnecessary to discuss this matter of 15 or 20 or 30 deg., conventional allowance, as opposed to the present five, and propositions that have been made for 5 and 10. The way it looks to me is that all the figures, taken together, do not point to any change with sufficient definiteness so that the change should be made.

I am, therefore, very pleased to know that we can in the future be satisfied to rate machinery on temperature rise alone, and I am also pleased to endorse Mr. Newbury's proposition that all other subject matter that relates to how the temperature rise was arrived at, be taken out of the rules, and perhaps be put into an introduction that would show the mental processes we went through in order to arrive at the values chosen.

With regard to Mr. Torchio's figure of 80 deg., I join the others in complimenting him on having so steadfastly stood for a certain figure throughout all the time that the rest of us have gone back and forth, sometimes have advocated one thing, and sometimes another, but we have returned to the original figure of ten years ago, and the rules as they now stand are exactly in accordance with the proposition which has been advanced and agreed to, if the foot-note No. 2 to §1005 of the 1921 Rules which refers to the 150 deg. is crossed out.

I would like to say one word about the distinction that I think should be observed between rating and application, and if we can have that distinctly and clearly in mind, I think even the difficulties of some of our foreign associates can be removed.

We now rate machines on temperature rise, and therefore the temperature rise determines the kw. or kv-a. that is marked on the nameplate, the question of "ambient temperature of reference" does not come into the matter, I think that what we want are rules for marking a machine of definite size, and therefore definite capacity, with a certain rating, *i. e.*, a certain kilowatt capacity, and then we should clearly know that it is well within the province of the user, if he pleases, to make some allowance for the fact that conditions of use may not be exactly the conditions that were established as the basis of the rating.

There may be some questions as to what extent anything of that kind should be done, but clearly, if the situation is such that the surrounding temperature is more than 40 deg., we should hesitate to put as much load on the machines as the rating calls for. On the other hand, I think in the interest of conservatism we should—when the ambient temperature is lower than the 40 deg. which has been established—hold in reserve that capacity which must, to some extent, be there, for a reasonable margin of safety.

P. Torchio: In answer to the question of Mr. Foster, I confirm his understanding that the 80 deg. rise is to be considered good practise, but the upper limit of good practise. Mr. Skinner's comments on the copper temperatures of the machines Nos. 4 and 5 are correct, but perhaps the figures I have given may still represent the actual maximum temperatures because since the paper was printed I found that the assumed constant of 2½ per cent increase per 1000 volts computed on the rise of the detector between coils is in fact excessive, a constant of about $1^2/_3$ per cent being closer to the average of result of several tests on machines especially equipped with exploring detectors in contact with the copper.

Mr. Wallau's valuable contribution fittingly supplements my paper. He, however, with some of the other speakers, emphasizes the importance of establishing a different standard for the temperature rise of the rotor windings. I am in full agreement with Mr. Dawson that a higher limit must be allowed for the rotor. From Mr. Wallau's presentation, a rise of 90 deg. would represent good and safe practise. I would endorse such a limit. It may be that the higher figure of 100 deg. suggested by Mr. Dawson may prove necessary for structural reasons. A little further study and cooperation should lead to an early agreement also on this point.

Referring to Mr. Wallau's and other speakers' comments on the life curve of fibrous insulation of Fig. 1, I do not know whether Class B insulation would have any similarity with the behavior of fibrous insulation. My reason for incorporating this Fig. 1 in the paper was not in an attempt to apply the results of fibrous insulation to Class B insulation. The only idea was that as in all windings we are always confronted with the presence of fibrous insulation either as binder of mica or in straight insulation of coils in the end turns, therefore, to cover fully the subject it was necessary to introduce the data given in Fig. 1. Incidentally, I call the attention of all engineers to the varied application that this fundamental information may have in all practical applications of the power industry.

F. D. Newbury: Mr. Foster questions the results obtained from the laboratory model described in my paper on Conventional Allowances, mainly because of the different manner in which heat is produced in the model, and in a generator. I do not see that this has any bearing on the conclusions reached. The problem was to establish the relations between certain temperatures inside and outside the insulation. To study the desired relations, a range of temperature values was produced. How this range of temperatures was produced was of no more consequence in this case than would have been the manner in which values of e. m. f. might be produced in a similar study of voltage drops in an electric circuit.

The particular values of temperature produced in this model were also of little significance so long as they covered a wide range. Thus, the fact, noted by Mr. Foster, that the difference between the copper temperature and core temperature in some of the experiments is greater than found in most generators is of no moment.

The model was used to establish certain temperature relations and a rational method of calculation for the conventional allowance. These relations and method were then checked by comparison with the results from generator tests. These generators were selected for test and tested under the supervision of Messrs. Foster, Williamson and the writer (each acting separately for generators manufactured by their respective companies.) Table IV, showing the comparison between calculated and tested values, is the criterion by which the work with the laboratory model should be judged. Considering the difficulties and errors inherent in machine temperature measurements, I believe Table IV shows a satisfactory degree of agreement.

Mr. Foster also points out that in fully one-half of the machines tested there was little difference between the inside temperature and the temperature measured between coils. This is true because these machines were of such dimensions (as to core length, insulation thickness, etc.) as to result in small temperature differences. Reference to Table IV will show that, in general, where the tested values are low, the calculated values are low also.

I do not believe that Mr. Foster has said anything that justifies any change in the conclusions reached as to probable values of conventional allowance, summarized in Fig. 10.

Mr. Torchio has used an empirical relation to calculate the conventional allowance that takes into account the single factor of rated voltage of the generator. The principal factors that determine the conventional allowance are the temperature difference between copper and outer coil surface, the temperature difference between top and bottom coil-sides (determined principally by eddy current factor) and the insulation thickness. In generators of less than 40-in. core length, the core length is also a factor. It is obvious that a relationship that neglects all but one of these factors can give reasonable results only if the other factors do not vary in generators of varying sizes, proportions and manufacturers.

This matter of conventional allowance has ceased to be of importance in specifying performance of machines, but is still of major importance in the work of standardizing committees in deducing allowable temperature rises from safe limiting temperatures of insulation. This, I hope, justifies this rather long discussion of what might be considered a purely academic question.

The agreement on 80 deg. as a satisfactory standard that has been expressed is very gratifying to all those interested in progress in this matter, and should make it possible for the Standards Committee to put this agreement in official form. The Standards Committee will, no doubt, also consider the question of rotor temperature limits. While this phase of the question has not received the same attention as has the armature winding temperature there has not been the same divergence of opinion and agreement should not be difficult.

Jean Canivet: In answer to Mr. H. G. Reist's remark concerning the satisfaction which was given in France by the American motors, I would like to emphasize the fact that the trouble we experienced with the French motors built according to our old rating was probably not due so much to the high temperature rise admitted than by the overload *without temperature limit* which was then allowed.

Higher Steam Pressures or Pulverized Coal?

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The author assumes a hypothetical power or public service steam plant of 100,000-kw. nominal capacity and compares the cost of operation of such a plant on a basis of 250 lb. pressure and 600 deg. fahr. total steam temperature, and 400 lb. pressure and 700 deg. fahr. total steam temperature, when fired by stokers and pulverized coal.

The results of the comparison indicate that, with much lower capital costs, even better thermal plant efficiency will pertain with the use of pulverized coal and the lower steam pressure than would be the case with the higher steam pressure plant, stoker fired.

TWO years ago, when the Edison Association of Illuminating Companies held its Annual Meeting at New London, Conn., the technical section developed a discussion as to what should be done with a view to lowering the cost of producing a kw-hour, which was at that time over 100 per cent greater than before the World War.

Various suggestions were made by engineers and others present, one statement being that the boiler pressure should be increased to 400 or 500 lb. Another official and engineer of a large public service corporation in the East quite emphatically made the statement that the only way to reduce these costs, in his opinion, would be to use pulverized coal and he predicted that in two years time this practise would begin to be generally used.

The writer, in discussing this subject, predicted that the excessive cost of the high-pressure idea would prevent a realization of lower costs, on account of the additional capital or fixed charges absorbing any gain which would be made from better thermal efficiency of the plant, and also said that rough figures would show that the desired results would be more likely to be obtained if only a portion of the additional expense involved was used in equipping the plant to use pulverized coal.

This question of higher pressures and temperatures is still a mooted one and is quite thoroughly discussed in a most excellent manner in a paper presented by Col. C. F. Hirshfeld, Chief Research Dept., of the Detroit Edison Co., before the Cleveland Section of the A. S. M. E. in March 1921. In this paper the author states that it is "his personal opinion that 700 deg. fahr. is about as high as we can safely go at present" and suggests a working pressure of steam at 400 lb.

As it is quite evident that there must be some point where the capital costs and fixed charges accompanying same will prohibit the reduction of the present kw-hr. cost from being benefited thereby, the author has made a study of the question from an investment and operating standpoint, comparing the present average practise as to pressures and temperatures with the above suggested 400 lb. pressure and 700 deg. final temperature. The basis on which the following estimates are made is as follows:

Capacity of plant, 100,000 kw.; consisting of four 25,000-kw. units and twelve 1600-h. p. boiler units (19,200 rated boiler h. p.) or approximately 5 kw. per boiler h. p.

As we are primarily interested more particularly in the *difference* in cost between the present average practise and the higher pressures, we have made a study of the various items entering into the costs of both suggestions, consulting with prominent manufacturers in order to obtain this information, which may be considered authentic and reasonable. For the lower pressures and temperatures we have adopted 250 lb. and 600 deg. fahr. temperature. For the higher, as above stated, 400 lb. and 700 deg. fahr. temperature. The items which are affected by the increase of pressure and the additional expense involved, due to the difference in pressure and temperature, are as follows:

(a)	Difference in cost of boilers and superheaters 19,200 h. p. at $13 per h. p., or $2.49 per kw., including freight and erecting charges	$249,600
(b)	" in economizers $4 per h. p. or $0.768 per kw.	76,800
(c)	" in steam turbines 100,000 kw. @ $2 per kw.	200,000
(d)	" in steam piping, forged valves and pipe covering at $2 per kw.	200,000
(e)	" in feed pumps and auxiliary apparatus 50 cents per kw.	50,000
	Estimated total difference in cost	$776,400

The average water rate of the turbines at 250 lb. pressure is assumed to be 10¾ lb. per kw-hr. and at 400 lb. pressure, 10 lb. per kw-hr., and an allowance of 5 per cent for additional power or steam for auxiliaries.

In the operation of the plant we have adopted an annual load factor of 40 per cent and a fair average bituminous coal has been assumed in both cases of 13,000 B. t. u., and 8 per cent of ash and the combined boiler furnace and economizer efficiency with stokers at 78 per cent, and with pulverized coal an equivalent efficiency of 85 per cent. The following costs have been used:

Cost of coal delivered $5 per long ton.
Cost of power ¾ cent per kw-hr.
Cost of common labor 40 cents an hour.

In the operating costs we have omitted taking into consideration the firing room labor, as these items would be practically identical in either case.

With the above items fixed, the steam requirements

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per hour for the 250-lb. pressure plant will be 451,500 lb., which translated into steam per hour from and at 212 deg. is equivalent to 569,793 lb. For the 400-lb. pressure plant these figures are 420,000 lb. and 547,260 lb. respectively.

Additional data may be determined from the foregoing as follows:

Item	250 Lb. Press. Plant Col. 1 Stoker fired	 Col. 2 Pulv. coal fired		Lb. Press. Plant Col. 3 Stoker fired	 Col. 4 Pulv. coal fired
(1) lb. coal per kw-hr.	1.36	1.25		1.31	1.214
(2) B. t. u. per kw-hr.	17680	16250		17030	15782
(3) Thermal eff. of plant-per cent	19.31	21.20		20.22	21.75
(4) Evap. per lb. coal from and at 212 deg. fahr.	10.43	11.27		10.43	11.27
(5) Fuel, tons per hr.	24.40	22.36		23.42	21.23
(6) Fuel cost per hr.	$122.00	$111.80		$117.10	$106.15
(7) Fuel cost per day	$2928.00	$2683.00		$2810.40	$2547.60
(8) Repairs ($1.50 per rated h. p. per year) per day	78.80		Pulv., dyring, repairs, labor, power, conveying and air supply 34c. ton*	78.80	
(9) Power for operating stokers, air supply, coal handling 4 per cent	117.00	204.00		117.00	198.22
(10) Fixed charges 12 per cent per yr. on $422,400 incl. coal bunkers and conveying and ash handling, stokers and air supply	138.00	141.00	Fixed chgs. pulv. coal plant, conveying system, bunkers, coal burning equip. air supply ash handling. Cost $476,000 inc. $60,000 for bldg.	138.00	141.00
(11) Ash removal 48 tons @ 25 cents	12.00	4.00	4 tons day av.	12.00	4.00
(12) Total cost per day, Items 7, 8, 9, 10 and 11	A-$3273.80	B-$3032.20		C-$3156.20	D-$2890.82
			Additional fixed chgs. @ 12 per cent. (See below)—per day	250.60	250.60
			Additional maintainence charges (See below) per day	21.25	21.25
			Actual total daily costs Col. 3 and 4	C′ 3428.05	D′ 3162.67

*These costs are based on pulverizing thousands of tons of bituminous coal and are, consequently, accurate. The items are as follows: Per net ton

Repairs—complete system	8	cents per ton
Power for all operation @ ¾ cents Kw-hr. (17 Kw-hr.)	12¾	" " "
Drying	6¼	" " "
Labor	7	" " "
Total	34	" " "

of operation as compared with pulverized coal on the low-pressure plant will be over $144,000 more per year and the thermal efficiency of the plant will be better with pulverized coal (17030 − 16250) by 780 B. t. u. per kw-hr., or reduced to percentage of B. t. u. in the coal utilized, the difference is nearly 1 per cent (21.20—20.26).

The cost of operation per diem in Col. 3, letter *C*, $3156.20, is not entirely complete as to this cost should be added the additional fixed charges due to the cost of the 400-lb. pressure plant as compared with the 250-lb. pressure plant, which, as previously shown will be $776,400. The per diem interest charges on this amount at 12 per cent equals $250.60.

Furthermore, there will be additional maintenance costs, due to the higher pressures and superheat, which may be taken as 1 per cent. The per diem cost of this item will be $21.25. These two daily costs added to the above item *C* is $3156.20 + 250.60 + 21.25 equal *C′* $3428.05. This is consequently, the total daily operating and fixed charges cost of the plant, so far as it refers to the furnace equipment, for the 400-lb. pressure plant.

Comparing this with the daily operating costs of the 250-lb. pressure plant fired with pulverized coal, Col. 2, Item 12, *B*—$3032.20, it will be noted there is a difference of $395.85 which constitutes the saving which would be effected by the use of pulverized coal and this is equal to $144,485 per year.

These figures demonstrate therefore, that under the same operating conditions the high-pressure cost

The estimate shows that the pulverized coal plant and necessary storage and burning equipment, auxiliaries and distributing system, etc. can be built in a substantial manner for approximately $476,000 (at present prices, Dec. 1921), of which $60,000 is allowed for a separate building (42 ft. by 144 ft.) for the milling and drying plant, having a capacity of 750 to 800 net tons of pulverized coal per day. This cost is only slightly more than the complete stoker equipment with distributing system, auxiliaries etc. installed. The costs of these equipments would be the same for both the 250 lb. and 400 lb. pressure plants.

The question might be raised as to the basis on which these estimates have been made in regard to thermal, boiler and furnace efficiencies. The author believes he is quite safe in stating that at the present time there is no plant in this country at any rate, operating on a B. t. u. basis of 17,680, stoker fired, as shown in Column 1 of above tables, although plans have been laid down for one or two power houses not yet in operation to give these results, so that this figure would indicate the best possible practise that can be obtained under the assumed load factor and other conditions of a plant of this size and pressure.

On the other hand, actual performance of boilers fired with pulverized coal in power plant service indicates that there is no difficulty in operating under these load conditions at the 85 per cent efficiency we have used for the basis of our calculations, which, as shown in Column 2, is equivalent to 16,250 B. t. u. per kw-hr. or 1¼ lb. of coal, containing 13,000 B. t. u.

In the appendix there is a record of some pulverized-coal-fired boiler tests which show a higher combined efficiency than we have assumed.

The final conclusions are:

(a) It will cost a great deal less money to equip and use pulverized coal in power plants in order to obtain the highest efficiency and the lowest operating costs than it would to use high pressure of 400 lb. and high superheat of 700 deg. final.

(b) That lower B. t. u. per kw-hr. and higher over-all thermal efficiency will be obtained by substituting pulverized coal firing in lieu of any other known method using the moderate high pressure and superheat in common practise today, compared with higher pressures and temperatures.

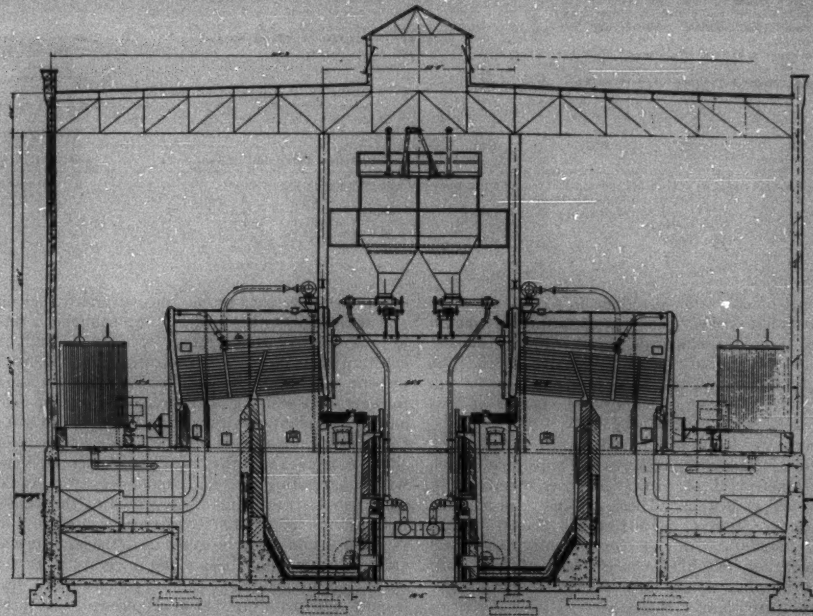

Fig. 1—Cross-Sectional View of Two 1308-H.P. Edgemoor Boilers

Arranged for burning pulverized Illinois coal.

(c) That the benefits accruing from the net difference in station water rate between the present practise as to pressure and temperatures and the higher pressures and temperatures are comparatively small and do not warrant the excessive additional first cost and yearly fixed charges for the higher pressures and superheat.

(d) That the cost per short ton of coal handled and burned by stokers in the 250-lb. pressure plant (exclusive of the cost of the coal) will be 52 cents and with pulverized coal 58 cents. For the 400-lb. pressure plant this cost would be increased to 95 cents per ton with stokers, which increase is due principally to the additional fixed charges over the 250-lb pressure plant.

Appendix

TESTS OF PULVERIZED COAL FIRED BOILERS MADE IN ACCORDANCE WITH THE STANDARD A. S. M. E. BOILER CODE

The equipment consists of a 1306-h. p. four-pass horizontal water tube Edgemoor boiler with 4-in. Fuller feeders and 4-in. flared type Fuller burners, located in a horizontal position, all as shown in the accompanying illustration.

The furnace conditions were most excellent and did not result in the formation of any slag. The furnace was not cleaned out during the time these two tests were run. There were but a few hours time between the finishing of No. 3 test of 48 hours and No. 4 test of 48 hours. The boiler was kept on the main steam header and no special efforts were made to obtain high efficiency. The boiler tubes had not been turbined for sometime before the tests were conducted, neither had the outside of the tubes been washed out except as they were blown every day with soot blowers.

DATA AND RESULTS OF EVAPORATIVE TESTS NOS. 3 AND 4

1. Test of Edgemoor Boiler No. 1.
To determine efficiency of boiler furnace and superheater.
Test conducted by Fred. Darnbrook and A. Hoffman
Ralph Galt and R. A. Kleppinger.
2. Edgemoor watertube boiler No. 1.
3. Powdered coal furnace.
4. Combustion space 9057 cubic feet.
5. 13057 sq. ft. water heating surface.
6. superheating surface.
7. total heating surface.
8. Date—Boiler Test No. 3 First half—June 30th & July 1st, 1921.
Second half—July 1st and 2nd.
Boiler Test No. 4 First half—July 5th and 6th.
Second half—July 6th and 7th.
9. Duration—Boiler Test No. 3.
First Half —24 hr. 53 min.
Second Half—23 hr. 25 min.
Average —48 hr. 8 min.
Boiler Test No. 4.
First Half —24 hr. 5 min.
Second Half—23 hr. 45 min.
Average —47 hr. 50 min.
10' Illinois coal powdered.

BOILER TEST NO. 3
HEAT BALANCE BASED ON DRY COAL

	First half		Second half		Average
	B. t. u.	Per Cent	B. t. u.	Per Cent	Per Cent
A. Heat absorbed by boiler	9732	81.7	10062	84.2	82.95
B. Loss due to evaporation H_2O in coal	61	.5	46	.38	.44
C. Loss due to heat carried by steam formed by the burning of hydrogen	443	3.7	398	3.33	3.51
D. Loss due to heat carried away in dry flue gases	1040	8.7	1108	9.27	8.99
E. Loss due to radiation and unaccounted for losses	640	5.4	336	2.82	4.11
	11916	100.0	11950	100.00	100.00

ULTIMATE ANALYSIS OF COAL

	First half	Second half
Carbon	68.40	68.21
Hydrogen	4.17	4.07
Nitrogen	1.37	1.26
Sulphur	4.00	3.91
Oxygen	9.30	9.37
Ash	12.76	13.18
B. t. u. Dry Coal	11916	11950

BOILER TESTS NO. 3 AND 4

	Test No. 3			Test No. 4		
	1st half	2nd half	Average	1st half	2nd half	Average
Average Temperature and Pressures	24 hr. 53 min.	23 hr. 25 min.	48 hr. 8 min.	24 hr. 5 min.	23.75 hrs.	47 hr. 50 min.
11. Steam pressure by gage, lb. per sq. in.	263.46	264.2	263.8	267	266.7	267
a. Aneroid barometer				29.32	29.31	29.31
12. Temperature of superheated steam, deg. fahr.	280.34	584.7	582.5	600.8	596.1	598.4
a. Normal temperature of saturated steam, deg. fahr.	411	411	411	411.4	411.4	411.4
13. Temperature of feed water entering boiler, deg. fahr.	198.7	203	200.7	210.3	213.2	211.6
a. Temp. of feed water entering economizer, deg. fahr.	131	132.3	131.6	126.6	130.5	128.5
b. Increase of temperature due to economizer, deg. fahr.	67.7	70.7	69.1	83.7	82.7	83.2
14. Temperature of escaping gases,						
a. Temperature of gas below fourth pass, deg. fahr.	468	470	460	512	526	518.7
b. Temperature of gas entering economizer, " "	436	436	436	464	464	464
c. Temperature of gas leaving economizers, " "	220	240	230	259	268	263.3
d. Decrease of temperature due to economizer, deg. fahr.	216	196	206	205	196	200.5
15. Force of draft between damper and boiler,						
a. Draft in first pass, in. of water	0.02	0.0185	0.019	0.0625	0.055	0.058
b. Draft in fourth pass, in. of water	0.46	0.477	0.468	1.057	1.16	1.108
c. Draft entering economizer, in. of water	0.503	0.536	0.529	1.270	1.29	1.28
d. Draft leaving economizer, in. of water	0.706	0.777	0.741	1.908	1.94	1.93
16. State of weather,						
a. Temperature of external air, deg. fahr.	81	81	81	82	82	82
b. Temperature of air entering ash pit, deg. fahr.				121	121	121
c. Relative humidity of air entering ash pit,						
d. Room temperature, deg. fahr.			93	196	196	196
e. Temp. Feeder platform, deg. fahr.				110	108	109
Quality of Steam						
17. Number of degrees superheat, deg. fahr.	169.34	173.7	171.5	189.4	184.7	187.1
18. Factor for correction for quality of steam						
Total Quantities						
19' Total weight of coal as fired, lb.	157022	144078	302000	231352	220699	452051
20. Percentage of moisture in coal as fired, per cent	5.124	4.2	4.66	3.85	4.05	3.95
21. Total weight of dry coal, lb.	148975	138889	287864	222445	211760	434445
22. Ash, clinkers and refuse, (dry) per cent	13.137	13.395	13266	13.567	13.337	13.453
a. Withdrawn from furnace and ash pit,						
b. Withdrawn from flues, tubes and combustion space						
c. Blown away with gases						
d. Total						
23. Total combustible burned, lb.	129404	120278	249682	192255	183517	375782
24. Per cent of ash and refuse, based on dry coal, per cent	13.137	13.395	13.266	13.567	13.337	13.453
25. Total water fed to boilers, lb.	1278338	1232625	2509673	1908243	1870209	3787452

BOILER TESTS NO. 3 AND 4—*Continued*

	Test No. 3			Test No. 4		
	1st half	2nd half	Average	1st half	2nd half	Average
Average Temperature and Pressures	24 hr. 53 min.	23 hr. 25 min.	48 hr. 8 min.	24 hr. 5 min.	23.75 hrs.	47 hr. 50 min.
26. Total water evaporated, lb.	1278678	1232625	2509673	1908243	1879209	3787452
27. Factor of evaporation, based on temperature of feed water entering boiler	1494135	1440938	2955073	2229209	2185332	4414541
a. Total equiv. evap. from and at 212 deg. fahr., lb.	1.1685	1.169	1.1687	1.1682	1.1629	1.1655
28. Factor of evaporation, based on temperature of feed water entering economizer	1.2395	1.24	1.24	1.2545	1.2481	1.2513
a. Total equivalent evaporation from and at 212 deg. fahr., lb.	1584921	1528455	3113376	2393890	2345440	4739330
Hourly Quantities and Rates						
29. Dry coal per hour, lb.	5971	5973	5972	9080	8916	8998
30. Coal as received, per hour, lb.	6293	6235	6274	9443	9292	9368
31. Water evaporated per hour, lb.	51387	52982	52140	77887	79124	78495
32. Equivalent evaporation per hour, from and at 212 deg. fahr., lb.	60045	61934	61282	90988	92013	91492
33. Equivalent evaporation per hour, from and at 212 deg. fahr., per square foot of heating surface, lb.	4.59	4.74		6.96	7.05	7.00
Capacity						
34. Evaporation per hour from and at 212 deg. fahr., lb.	60045	61934	60936	90988	92013	91492
a. Boiler horse power developed, h. p.	1740	1795	1766	2637	2667	2651
35. Rated capacity per hour from and at 212 deg. fahr., lb.	45057	45057	45057			
a. Rated boiler horse power, h. p.	1306					
36. Percentage of rated capacity developed, per cent	131.2	137.4	135.2	201.9	204.2	203.0
a. Flow meter, indicating h. p.	1332					
Economy						
37. Water fed per pound of coal as fired, lb.	8.143	8.5	8.31	8.248	8.51	8.3746
38. Water fed per lb. of dry coal, lb.	8.51	8.87	8.71	8.58	8.874	8.728
39. Equivalent evaporation from and at 212 deg. fahr. per lb. of dry coal as fired, lb.	9.515	9.93	9.7	9.63	9.90	9.762
40. Equivalent evaporation from and at 212 deg. fahr. per lb. of dry coal, lb.	10.029	10.37	10.18	10.02	10.319	10.167
41. Equivalent evaporation from and at 212 deg. fahr. per lb. of combustible, lb.	11.546	11.97	11.75	11.594	11.908	11.748
Efficiency						
42. Calorific value of 1 lb. of coal as fired, per analysis, B. t. u.	11310	11449	11380	11465	11581	11522
43. Calorific value of 1 lb. of dry coal, per analysis, B. t. u.	11916	11950	11932	11924	12070	11995
44. Calorific value of 1 lb. of combustible, B. t. u.	13720	13799	13762	13782	13927	13853
45. Total heat absorbed by boiler,						
a. Total heat in steam, B. t. u.	1302	1304	1303	1312	1309.7	1310.86
b. Total heat absorbed per lb. water fed to boiler, B. t. u.	1135.3	1133	1134.3	1133.7	1128.5	1131.2
c. Total heat absorbed per lb. water fed to economizer, B. t. u.	1203	1204	1203.4	1217.4	1211.2	1214.2
46. Efficiency of boiler, furnace and superheater, based on coal as received, per cent	81.7	84.1	82.8	81.56	82.92	82.23
47. Efficiency of boiler, furnace and superheater, based on combustible, per cent	81.66	84.1	82.8	81.62	82.97	82.19
48. Efficiency of boiler, furnace, superheater and economizer, based on coal as received, per cent	86.6	89.3	87.9	87.5	89.001	88.38
Gas Analysis—by Volume						
49. Fourth pass,						
a. Carbon dioxide	14.03	13.4	13.7	13.73	13.58	13.655
b. Oxygen	4.76	5.475	5.11	5.355	5.48	5.417
c. Carbon monoxide	0.013	0.00	0.00	0.041	0.0014	0.0214
d. Nitrogen (by difference)				80.874	80.8386	80.85
50. Economizer Inlet,						
a. Carbon dioxide				11.57	11.47	11.52
51. Economizer Outlet,						
a. Carbon dioxide				10.10	10.23	10.16
Analysis of Coal						
52. Moisture, per cent	5.125	4.2	4.55	3.85	4.05	3.95
Ash, per cent	13.137	13.395	13.255	13.567	13.337	13.454
B. t. u. per lb. of dry coal, B. t. u.	11916	11950	11932	11924	12070	11995
B. t. u. per lb. of coal as received, B. t. u.	11310	11440	11380	11465	11581	11522
Sulphur, per cent (separately determined)	4.23	3.81	4.03	3.997	3.422	3.709
Additional Data						
53. Rev. per min. feeder screws, No 1 West	114	115	115	160	160	160
No. 2	99	96	98	160	138.7	149.3
No. 3	108	117	113	145	142	143.5
No. 4, East	121	117	119	158	165	161.5
54. Rev. per min. economizer fan	119	146		279	278	278.5

Discussion

Philip Torchio: I would like to ask Mr. Scheffler why contrast higher steam pressures against pulverized coal. Why not both? What is inconsistent between the two? The pulverized coal situation as affecting large cities is mostly a question of improving means to handle the ashes that come from the stacks. Until that problem has been definitely solved, it would be practically inadvisable to attempt, in a densely populated district, to install on a very large scale a system of coal burning that would scatter a considerable amount of ashes in the territory surrounding the station.

The question of using higher steam pressures is of vital importance. I do not know that the figures of cost of present standard pressure boilers and piping would be much exceeded if we had a fully developed system of high pressure machinery, and the boiler makers would standardize production on higher pressures that they have been doing. In that event, the increased cost of the equipment might not be as great as shown by the figures of Mr. Scheffler.

It seems to me that the difference in saving of less than five per cent between low pressure and high pressure is probably somewhat low, and that a larger saving would be realized in practise.

Abroad, there is now a station operating at 450 lb. pressure and 750 deg. steam temperature. We should look to the performance of that station with a great deal of interest.

Wm. McClellan: I have been in contact with pulverized fuel a great deal, and the burning of it at the mine. I could not quite see the point involved in the title of the paper "Higher Steam Pressures or Pulverized Coal." If there is any economy in high steam pressures, the economy is there, and if there is any economy in pulverized fuel, it is there.

My idea, without looking into the question of ashes, is that it can be cared for, and with some profit. So far as blowing out the ashes is concerned, that is not a vital feature of the problem. If you choose coal at $5.00 a ton, you may come out all right. There are lots of plants in this country which will be built to order, using cheap fuel.

Of course, if you have not sufficient load factor to work out all the advantages of economy, and if you do not use the more efficient methods long enough, you do not derive the greatest benefit, but in any event, it is no more expensive, and if it is no more expensive, this particular point vanishes. I do not quite see the distinction, first of all, between the antithesis which has been set up in the title of the paper, nor do I see that any one particular problem with a fixed coal price, and with a high one, without much discussion of the load factor, answers the question very definitely.

F. A. Scheffler: The President answered Mr. Torchio's question so far as the ash disposal from the stacks is concerned, but this is not an important part of the proposition. If the location of the plant is such that the fine ash coming out of the stacks is disturbing to the surrounding country, prevention can be taken care of more readily and with less expense than would be the case with cinders coming from stokers from the stacks.

The title of this paper probably should have been "Higher Steam Pressures and Pulverized Coal" as it is a little misleading as it now stands. The writer in dealing with this question had more particularly in mind the possibility of equipping low-pressure plants in such a way that they would compare favorably with the more expensive and higher pressure plants, even showing better efficiency with lower operating expenses. This is clearly shown in Column 4, page 347 as that column deals with a plant which was fired with pulverized coal, using higher steam pressures.

In order to really appreciate and understand fully the principal features developed in this paper, it is necessary to read it in toto carefully and I judge, from the remarks made by the President, as well as the other speakers in the discussion, that they have not done this, otherwise they would have noted that the answers to the questions they brought up were practically taken care of in the paper.

Rating of Cables in Relation to Voltage

SUMMARIZED HISTORY OF PUBLISHED KNOWLEDGE BEARING UPON THE PERFORMANCE OF INSULATION UNDER ELECTRIC STRESS

Prepared by the Subcommittee on Wires and Cables of the Standards Committee

INTRODUCTION

UNDER the auspices of the Wires and Cables Subcommittee of the Standards Committee of the Institute, a symposium on the rating of cables with reference to heating due to conductor losses only, was held during the 1921 Midwinter Convention of the Institute with the object of checking the Institute's standards in regard to permissible operating temperatures for cable insulation. That is, the discussion was limited to the matter of the safe maximum operating temperature of low-voltage cables with negligible dielectric losses.

The six papers presented and the discussion thereon did not show any general agreement on the point at issue. In fact, the divergence of views was still just about as great as had been previously suspected, judging from views expressed informally in committees and elsewhere. The great importance of the subject was, however, emphasized and the need for sufficient comprehensive research work to establish the fundamental physical facts involved was made evident. The result has been the inauguration of a comprehensive research on this and other fundamental cable problems by the Research Department of the Massachusetts Institute of Technology under the auspices of the Paper-Insulated-Cable Research Committee, which is a sub-committee of the A. I. E. E. Transmission and Distribution Committee, the N. E. L.A. Underground Systems Committee and the A. E. I. C. Committee on Electricity Distribution and Use.

It is believed that a similar situation exists with reference to the rating of cables with respect to voltage and the Subcommittee on Wires and Cables of the Standards Committee has therefore arranged this symposium on the rating of cables with respect to voltage only, which will be a corollary of the symposium held last year on cables with respect to heating only (*i. e.*, current only). It is further believed that a discussion of the matter at this time is particularly timely, both because of a demand for the standardization of insulation thickness for impregnated paper cables and because of the many proposals under consideration for cables to operate at much higher voltages than any now in extensive use. It is hoped that the papers presented and the discussion thereon will enable cable engineers to more efficiently design and operate cables and thereby utilize more effectively the investment which the cables represent.

CONTENTS

I. Geometric relations which affect dielectric stresses.
II. Dielectric failure of air
III. Ionization of gas in solid insulation
IV. Dielectric failure of transformer oil.
V. Electrical properties of petrolatum.
VI. Residual charge, power factor and associated effects.
VII. Grading of insulation.
VIII. Miscellaneous data.

I. Geometric Relations which Affect Dielectric Stress.

JONA, E. (*Trans. Int. Elect. Cong.* 1904, vol. 2, p. 550) showed that the electric stress in a dielectric between two concentric conducting cylinders, which is the simplest geometric representation of a single-conductor cable, follows the law.

$$H = \frac{E}{x \log \epsilon \frac{R}{r}}$$

where

H = stress in kv. per cm. at any point x cm. from the axis
E = difference of potentials between cylinders, in kv.
R = radius of outer cylinder, cm.
r = radius of inner cylinder, cm.

LEVI, CIVITA, (*Rendiconti Circolo Matematico di Palermo*, vol. XX, 1905, part 1, p. 173) gives formula for maximum stress including the effect of stranding.

THORNTON, W. M. AND WILLIAMS, O. J. (*Electrician* 1909, vol. 63, p. 833) gave experimentally-determined diagrams of electrostatic force both for round and sector triplex cables.

DEUTSCH, W. (*E. T. Z.* 1911, vol. 32, p. 1175) derives approximate formula for the maximum stress including the effect of stranding.

GORGAS, BENISCHKE, PETERSEN ETC. (*E. T. Z.* 1913, vol. 34, pp. 637, 783, 984, 1186, 1354) correspondence and discussion of stress at conductor surface, especially on approximate formula for stresses between parallel cylinders.

MIDDLETON, W. I. AND DAWES, C. L. (TRANS. A. I. E. E. 1914, vol. 33, p. 1185) discussed the logarithmic formula, and showed that the stress at the surface of a conductor was a minimum when $d = D/2.72$, where d is the diameter over the conductor, D is the diameter over the insulation, and 2.72 is the Naperian logarithmic base e. There is also a discussion of overstressing of cables.

RUSSELL, A., (*Proc. Phys. Soc.* London, 1919, vol. 33, p. 111) derives formula for stress between parallel cylinders.

ATKINSON, R. W., (TRANS. A. I. E. E. 1919, vol. 38-2, p. 971) developed a method of estimating the stresses in a triplex cable.

DEL MAR, W. A. (TRANS. A. I. E. E. 1919, vol. 38-2, p. 1018) gave diagrams of equipotential and stress lines in round and sector triplex cables.

DAVIS AND SIMONS (JOURN. A. I. E. E. Jan, 1921, p. 12) published tables of maximum stresses based on Atkinson's method.

EMANUELI, LUIGI (*L'Elettrotecnica* 1921, vol. 8, p. 573) gives experimental determinations of stresses in three conductor cables.

II. Dielectric Failure of Air.

STEINMETZ, C. P. (TRANS. A. I. E. E. 1893, vol. 15, p. 281) suggested that the diameter of a corona in air is such that the corona reduces the electric intensity (or potential gradient) at its boundary, to the constant value of the electric strength of air.

RYAN, H. J. (TRANS. A. I. E. E. 1904, vol. 21, p. 275) found

Presented at the Annual Convention of the A. I. E. E., Niagara Falls, Ontario, June 26-30, 1922.

that the apparent dielectric strength of air around a wire varies with the diameter of the wire.

Jona, E. (*Trans. Int. Elect. Cong.* 1904, vol. 2, p. 550) said that the diameter of the air corona, for a given arrangement of conductors, is independent of the size of wire and depends only on the voltage.

Townsend, J. S. (*Trans. Int. Elect. Cong.* St. Louis 1904, vol. 1, p. 106) said that free ions exist in air which are accelerated in their motion when subjected to electric stress. When they attain a certain speed, they knock electrons from their atomic orbits thus liberating the electrons and converting the atoms into ions.

Whitehead, J. B. (Trans. A. I. E. E. 1910, vol. 29-2, p. 1183) said that as the logarithmic law for concentric cylinders indicates different stresses at a given distance from the axis, with different conductor diameters and as corona observations indicate the same stress, the logarithmic law must fail when corona is present and therefore the air carrying a corona must have a relatively high conductivity.

Hayden, J. R. and Steinmetz, C. P. (Trans. A. I. E. E. 1910, vol. 29-2, p. 1125) showed that the disruptive discharge through a dielectric requires not merely a sufficiently high voltage, but also a definite minimum amount of energy.

Whitehead, J. B. (Trans. A. I. E. E. 1910, vol. 29-2, p. 1159) said that an electron requires an intensity of 170 kv. per cm. to give it sufficient velocity to break up a molecule by collision, and concluded from this that the ionizing agents, in the ionization by collision which creates corona, must be of atomic or molecular dimensions. Such ions require only 30 to 40 kv. per cm. He showed that there is no dielectric loss in air until the corona point is reached, that the electric strength of air is independent of the material of the electrode, that the corona voltage is lowered by surface impurities, that the corona has high conductivity, and that most of the dielectric loss takes place beyond it.

Ryan, H. J. (Trans. A. I. E. E. 1911, vol. 30-1, p.1) applied th electron theory to the explanation of corona loss.

Whitehead, J. B. (Trans. A. I. E. E. 1911, vol. 30-3, pp. 1883-1885) gave evidence that corona is due to the liberation of ions from neutral molecules when the latter suffer collision with free ions moving under the impulse of an electric field.

Peek, F. W. (Trans. A. I. E. E. 1911, vol. 30-3, p. 1889) showed that the corona loss around a wire varies as the square of the excess voltage above the voltage at which corona starts. He also showed that the electric strength of air is about 30 kv. per cm. and that corona starts when this intensity is attained at a distance of 0.301 $\sqrt{r}$ cm. from the surface of the conductor. This distance is called the energy distance. A finite thickness of air must be under a stress of 30 kv. per cm. or more before breakdown occurs.

Peek, F. W. (Trans. A. I. E. E. 1912, vol. 31-1, p. 1051) showed that the energy distance for corona around cylindrical wires varies with the relative air density s and is.

$$0.301\sqrt{\frac{r}{s}}\ \text{cm.}$$

Peek, F. W. (Trans. A. I. E. E. 1913, vol. 32-2, p. 1767) showed that the energy distance for spheres is

$$0.54\sqrt{\frac{r}{s}}$$

and that where the electrodes are placed closer together than the energy distance, the apparent dielectric strength increases.

Peek, F. W. (Trans. A. I. E. E. 1915, vol. 34-2, p. 1857) showed that the time lag of breakdown is conveniently measured in micro-seconds, and that the lag varies with the electrode and is a maximum for the needle gap and a minimum for a uniform field or for a sphere gap.

Whitehead, J. B. and Brown, W. S. (Trans. A. I. E. E. 1917, vol. 36, p. 169) showed that corona appears at a lower value when the wire is positive than when negative, the maximum excess of negative over positive (which occurred for small diameters) being 6.3 per cent. The values for alternating current coincide with those for negative continuous voltage. Evidences in favor of Townsend's theory of ionization by collision are given.

Peek, F. W. (Dielectric Phenomena, p. 84) says that air between concentric cylindrical electrodes has its maximum electric strength when the diameter ratio is 3 instead of 2.72, the value to be expected if the logarithmic formula were strictly applicable. This he deduces from the energy-distance and checks experimentally.

Peek, F. W. (Dielectric Phenomena, p. 85) says that the corona in air seems in effect to be either a series resistance or it grades or distributes the flux density when the conductor configuration is such that corona occurs before spark-over. He said that under this condition spark-over between concentric cylinders, does not occur when $\frac{R}{r_1}$ = critical ratio, where r_1 = radius of corona, and R = radius of outer cylinder.

III. Ionization of Gas in Solid Insulation

Fessenden, R. F. in 1898 made experiments which showed the danger of air bubbles in solid insulation.

Perrine, F. A. C. (Trans. A. I. E. E. 1902, vol. 19, p. 1067) said that the failure of cable insulation is sometimes due to the presence of spaces filled with rarefied gases.

Petersen, W. (*Archiv. fur Elektrotechnik*, 1912, vol. 1, p. 28) called attention to the fact that air films in a dielectric of specific capacity K, are subjected to a stress of K times that in the surrounding medium, and that ionization may therefore occur therein at comparatively low voltages. He also said that ions are shot from these films into the surrounding medium.

Dubsky, F. (Trans. A. I. E. E. 1919, vol. 38-1, p. 537) measured the dielectric strength of thin air films between glass plates. He then applied these data theoretically to assumed gas spaces in solid dielectrics and showed the possible conditions under which ionization was likely to occur.

Shanklin, G. B. and Matson, J. J. (Trans. A. I. E. E. 1919, vol. 38-1, p. 489) measured the ionization voltage in actual insulation designs by the dielectric loss method. In the case of coil insulation, such as varnished cambric and mica-paper, they give evidence showing that ionization not only occurs in the entrapped gas spaces but that it can cause serious damage. In the case of paper-cables, evidence is given showing that a true ionization occurs. However, the exact nature of this ionization, its position, and the possibilities of serious damage are not clearly shown.

IV. Dielectric Failure of Transformer Oil

Tobey, H. W. (Trans. A. I. E. E. 1910, vol. 29, p. 1189) after discussing generally the testing of oils for dielectric strength, gives particulars of the influence of moisture on this property.

Hendricks, A. B. (Trans. A. I. E. E. 1911, vol. 30-1, p. 167) showed that moisture has an important effect in reducing the dielectric strength of insulating materials. In the case of transformer oil, if E be the kilovolts producing breakdown between 0.5 in. discs, 0.2 in. apart, and x = parts of water in 10,000, by volume, then

$$E = \frac{19.2}{x^{0.284}}$$

Hendricks, A. B. (Trans. A. I. E. E. 1911, vol. 30-3, p. 1975) stated that transformer oil between concentric cylindrical electrodes has its maximum electric strength when the diameter ratio is about 7 instead of 2.72, the value to be expected if the logarithmic formula were applicable. He also said that the dielectric strength of transformer oil is increased by mechanical pressure, an increase from 0 to 200 lb. per sq. in. increasing the dielectric strength 50 per cent. This, by the electron theory, is due to the decreased mobility of the ions under pressure.

Peek, F. W. (*General Electric Review*, Aug. 1915, vol. 18, p. 821) states that a phenomenon similar to corona in gases also takes place in liquid insulations, such as oil, due to tearing apart of the molecules of the oil or occluded gases. It seems that occluded gases often take an important part in supplying initial ionization. The effect of moisture is also pointed out.

Peek, F. W. (Trans. A. I. E. E. 1915, vol. 34-2, p. 1857) found that the time lag is much greater for oil than for air.

Hirobe, T. Ogawa, W., and Kubo, S. (*Report*, Electrochemical Laboratory Tokio, Japan, 1916, report No. 25-3) showed that dust and fibrous matter in oil impair its insulating power, and that moisture has but little effect without absorbing media.

Peek, F. W. (Dielectric Phenomena, 1920) showed that the dielectric strength of transformer oil can be increased by the use of baffles which confine the motion of the ions, impurities, etc.

Peek, F. W. (Dielectric Phenomena, 1920) showed that transformer oil under electric stress exhibits properties similar to air. He showed that the energy distance is about $1.2\sqrt{r}$ cm. *i.e.*, about four times that of air, and that with such an energy distance, corona and spark-over voltages wil be equal for ratios of $\frac{R}{r}$ up to at least 300.

Hayden, J. L. R. and Eddy, W. N. (Jour. A. I. E. E., Feb. 1922) show how the failure of transformer oil depends upon the presence of impurities. They compare the number of failures at each voltage with the number to be expected according to the curve of probability, and find that they do not agree.

V. Electric Properties of Petrolatum.

Malcles, L. (*Comptes Rendus* 1910, vol. 151, p. 63) furnished the idea that the behavior of petrolatum in an electric field is the result of free ions which are mobile when the petrolatum is fluid and immobile when it is jelly.

VI. Residual Charge, Power Factor and Associated Effects.

Faraday, M. (Experimental Researches in Electricity, 1839) was probably the first to notice the phenomenon of residual charge.

Hopkinson, J. (*Phil. Trans.* 1877, vol. 167, p. 599) showed that the residual charge is proportional to the exciting charge and gives results on experiments performed on several kinds of glasses, showing the effects of temperature. He noted that the residual charge in a Leyden jar can be promoted by tapping the dielectric, an indication that such charges are due to some internal polarization which is affected by shock.

Ayrton, W. E. and Perry, J. (*Proc. Royal Society* 1878, vol. 27, p. 238) said that dielectrics exhibit an increase of strain under a prolonged constant dielectric stress and said that this was due to the "viscosity of the dielectric". They explained viscosity on the basis of the presence of comparatively conducting particles in "dielectrics of heterogeneous composition" and suggested that dielectrics and metals might owe their different properties to the presence of rotary molecular motion in the one and motion of translation in the other.

Muraoka, H. (*Wied. Ann.* 1890, vol. 40, p. 329) found that while paraffin and xylol showed practically no residual charge when separate, a layer of xylol on a layer of paraffin showed residual charge.

Maxwell, J. C. (A Treatise on Elec. and Mag. 2nd ed. 1881, vol. 1, chap 10, p. 412) proved theoretically that a compound dielectric built up of layers of different non-absorptive dielectrics would exhibit both absorption and residual charge effect provided that the product $\rho\, k$ is different for each lamina. (ρ = resistivity and k = specific capacity.

Steinmetz, C. P. (*Elec. Eng.* 1892, vol. 13, p. 272) showed that the energy consumed by a dielectric medium under alternating electrostatic strain is directly proportional to the square of the intensity of the electrostatic strain or $H = k\, E^2$. Hence, whereas magnetic hysteresis follows the law of the 1.6th power, dielectric hysteresis follows the law of the square, that is, it acts just the same as a mere dead resistance connected into the circuit.

Bedell, F. and Kingsley, C. (*Phys. Rev.* 1894, vol. 2, p. 170) showed by the use of curves, the effects of a previous negative charge upon successive residual discharges, he effect of absorption upon the discharge curves, the effects of temperature on the resistance of oils and solid dielectrics.

Steinmetz, C. P. (*Elec. World* 1901, vol. 37, p. 1065) cited experiments on a paraffined paper condenser, showing that the dielectric loss is proportional to the square of the voltage and practically independent of the frequency. He suggested that the loss was largely due to mechanical motion of occluded air molecules under the influence of the alternating stress.

Drysdale, C. V. (*Electrician* 1901, vol. 46, p. 890) gave data on dielectric loss in cables and condensers, and called attention to its importance due to the energy loss being a continuing one regardless of the load. He also gave tables of losses in dielectrics, power factors, etc., for different types of mica condensers with varying pressures.

Torchio, Philip (*Trans. A. I. E. Cos.* 1902, pp 217-219, quoted in Trans. A. I. E. E. 1917, vol. 36 pp. 499-501) gave results of measurements of dielectric losses on long feeder cables installed, and stated that "the dielectric losses are approximately proportional to the frequency, to the square of the voltage and to a certain function of the temperature not yet determined. The temperature however, increases considerably the dielectric losses."

Skinner, C. E. (Trans. A. I. E. E. 1902, vol. 19, p. 1047) showed that dielectric loss varies with frequency, but not always in direct proportion. The variation from proportionality was especially marked at higher temperatures. He also showed that not only is the loss greater at high temperatures, but so is the rate of increase of loss.

Perrine, F. A. C. (Trans. A. I. E. E. 1902, vol. 19, p. 1067) said that work with cables has shown that a slight amount of moisture in the insulation will materially increase the heating and that heating of this character almost invariably results in final breakdown.

Monasch, B. (*Annalen d. Physik* 1907, vol. 22, p. 905) says that the loss varies strictly as the square of the impressed voltage up to the point of formation of corona and that in cables at ordinary frequencies, the loss is approximately proportional to the frequency.

Fisher, H. W. (Trans. A. I. E. E. 1907, vol. 26-2, p. 997) gave data on the dielectric loss in rubber compounds and showed that compounds containing a large amount of extractive matter may have lower losses than those containing small amounts.

Trauton, F. T. and Russ, S. (*Proc. Royal Soc.* 1907, vol. 20, p. 551) showed experimentally that the recovered (residual) charge does not follow an exponential law as derived by Maxwell, but a logarithmic law.

Shuddemagen, C. L. B. (*Prov. Am. Acad. of Arts & Sci.*, 1909, vol. 44, p. 467) showed that the current which forms residual charge, or in other words, the absorption current, is far from negligible when the charging interval is very small.

Hochstaedter, M. (*Elek. Zeit.* 1910, vol. 31, p. 467) reported that tests on impregnated paper cables showed the dielectric loss to be exactly proportional to the frequency. He found that the maximum voltage in each cycle occurs simultaneously with the zero value of the current, but the maximum current does not coincide with zero voltage. He made a "dielectric hysteresis loop" from oscillograms and deduced therefrom the capacity, residual charge and dielectric loss.

Decombre, L. (*Comptes Rendus*, 1911, vol. 152, pp. 315 and 1755) discusses dielectric loss in relation to polarization and makes some developments of Maxwell's theory. His reasoning, which is typical of that of several other physicists, is as follows:

The charge in a condenser is made up of two parts, one $k\, E$, due to an ether displacement and the other m, to a polarization of the dielectric, or $q = m + k E$. According to the theory of Lorentz,

$$a \frac{d^2 m}{d t^2} + C \frac{d m}{d t} + b m = E$$

where a, b, and c are positive coefficients. If the voltage E is alternating the term $\frac{d^2 m}{d t^2}$ which is proportional to f^2, where f is the frequency is negligible, unless the frequency is of the order of that of light. Hence

$$c \frac{d m}{d t} + b m = E$$

But the energy absorbed is $E\, d\, q$, i. e., $E\,(d\, m + k\, d\, E)$. For a complete period the energy lost, if assumed to be dependent on the polarization of the dielectric, therefore equals

$$\int_0^T E \; d\, m \text{ or } \int_0^T C \left(\frac{d\, m}{d\, t}\right)^2 d\, t$$

Hence, the alternate charge or discharge of a condenser causes a dissipation of energy proportional to the square of the polarization current, $\frac{d\, m}{d\, t}$.

Rayner, E. H. (*Jour. I. E. E.* 1912, vol. 49, p. 3) reported the results of an extended investigation to determine the relative effects of a short application of high test voltage or longer application of lower test voltage. He also gave considerable information about the effect of humidity and temperature on the dielectric strength of insulating materials. The paper has a bibliography on the subject of dielectrics, containing 300 references, dated from 1864 to 1912.

Walker, Miles (*Jour. I. E. E.* 1912, vol. 49, p. 71) showed that if curves be made with temperature for abscissas and watts for ordinates, one curve giving the power lost in the cable and the other the power dissipated, an increase of temperature will be cumulative if the dissipation curve is above the loss curve, and non-cumulative if the reverse is true.

Fleming, J. A. and Dyke, G. B. (*Jour. I. E. E.* 1912, vol. 49, p. 323) showed that two non-absorptive condensers of different capacities, each in series with a non-inductive resistance and the two connected in parallel, will act as a single condenser having absorption, if the products $c_1 r_1$ and $c_2 r_2$ are unequal. This paper and the discussion thereon, give a clear theoretical treatment of the subject and considerable experimental data to support the theory.

Addenbrooke, G. L. (*Electrician*, 1912, vol. 68, p. 829) showed by measurements at different frequencies that dielectrics may be considered to consist neither of capacities and resistances in series nor of capacities and resistances in parallel. He also showed that the loss in liquid dielectrics is independent of the frequency above a certain point whereas in solids it increases with the frequency, but not always according to a linear law.

Pungs, L. (*Archiv. f. Elektrotechnik* 1912, vol. 1, p. 329) showed that the dielectric losses in transformer oil are practically independent of the frequency. He concluded from this that the losses are due to ionic conduction rather than hysteresis. Resin oil showed similar properties the loss increasing but slightly with the frequency.

Addenbrooke, G. L. (*Electrician* 1913, vol. LXX, p. 673) gives data on dielectric loss in gutta-percha. He found the power factor to vary as follows with frequency.

Cycles	Power Factor Per Cent
46	4.0
12	5.5
6	6.3
3	7.2
1.5	7.5

Wagner, K. W. (*Ann. der Phys.* 1913, vol. 40, p. 817, and *Elek. Zeit.* 1913, vol 34, p. 1279, developed Maxwell's theory of residual charges arriving like Maxwell, and unlike Trauton and Russ, at an exponential equation for residual charge current. He showed that his theory is consistent with observed facts regarding the relation between power factor and frequency. He also showed that his theory leads to the possibility of more than one maximum of dielectric loss at various temperatures, this also being in accordance with observed facts.

Evershed, S. (*Jour. of I. E. E.* 1914, vol. 52, p. 51) says that in absorbent insulators the conduction is not normally through continuous filaments of moisture but by endosmose. He explains endosmose as a motion of films of water along the walls of an insulator due to the water being electropositive to practically all solid insulating materials and being therefore drawn through the pores of the solid toward its electronegative end, where a potential gradient is impressed on the solid. He explains the well-known time fall of insulation resistivity as being due to the spreading of moisture globules over internal surfaces of the solid insulation under the influence of endosmose, *i. e.*, normally the moisture exists in globules separated by dry internal labyrinth surfaces of solid, but when a potential gradient is applied, these globules spread over the surfaces of the labyrinth and reduce the resistance. When the potential gradient is removed, the films coalesce into globules causing the resistivity to rise. Under the influence of an alternating potential gradient, the globules do not have time to spread over the surfaces, but vibrate, causing a loss of energy. Evershed made a model insulator consisting of an inverted *V*-tube containing alternate drops of water and air, the ends of the tube being each set in a beaker. When a potential gradient was established between beakers, the drops of water spread along the walls of the glass tube, and the resistance characteristics were found to be similar to those of an absorbent insulator. When the potential gradient was raised, failure began in the form of sparking along the films from one drop to another.

Wagner, K. W. (*Elek. Zeit.* 1915, vol. 36, p. 111) developing Maxwell's theory of composite dielectrics shows by simple calculations that in a dielectric composed of two elements, one of which has resistivity r and specific capacity k and the other resistivity R and specific capacity K, the residual charge will be zero if $r\,k = R\,K$. He also suggested that the dielectric loss would be zero under these conditions.

Skinner, C. E. (*Jour. Franklin Inst.* 1917, vol. 183, p. 667) showed that the dielectric loss in transformer insulation follows the equation $W = k\,E^n$ where the constants have the following values:

Temperature Deg. Cent.	k	n
30	0.025	2.34
40	0.032	2.27
50	0.044	2.22
60	0.068	2.21
70	0.107	2.18
80	0.155	2.15

W = Watts lost and E = effective kilovolts.

Bang, A. F. and Louis, H. C. (Trans. A. I. E. E. 1917, vol. 36, p. 431) following the method suggested by Walker, developed a method of determining the influence of dielectric losses on the rating of cables. They determined dielectric losses by the heating effects and gave data on the emissivity of conduit lines.

Clark, W. S. and Shanklin, G. B. (Trans. A. I. E. E. 1917, vol. 36, p. 447) give formulas for calculating dielectric loss in three-phase cables, data on dielectric losses, resistivities and specific capacities. They showed that when an impregnated paper cable is bent, voids are created which become filled with gases from the volatilization of the oils, pp. 458-460. These reduce the resistivity at high voltages due to the ionization of the gases. A comparison of losses in old and new cables is given.

Atkinson, R. W. (Trans. A. I. E. E. 1917, vol. 36, p. 521) says that tests on impregnated paper cables at 25 and 60 cycles showed that the loss at 25 cycles is always somewhat less than at 60 cycles, and in some cases, is in almost direct ratio with the frequency. In other cases, there is little difference. Tests on a dried but unimpregnated paper lead cable showed the dielectric loss to be extremely low at all temperatures.

Swyngedauw, R. (*Revue Gen. d'Elec.* 1919, vol. 5, p. 283) said that tests on triplex cables indicate that the dielectric loss obeys the following law:

$$W = (a + b\,E)\,f\,C\,E^2$$

where a and b are constants, C is the capacity, f the frequency and E the voltage.

VII. Grading of Insulation

Jona, E. (1898) made graded cables and exhibited them at Milan.

O'Gorman, M. (*Journal I. E. E.* 1901, vol. 30, p. 608) showed that to get uniform stress in a dielectric, the product $K\,x$ must be constant where K is specific capacity and x = radial distance from the axis of the cable.

Morris, J. P. (*Jour. I. E. E.* 1907, vol. 40, p. 50) claims to have first suggested the use of intersheaths in the cable installation, in order to anchor the potential of the various layers of insulation in any manner desired by means of connections outside of the cable.

Russell, A. (*Jour. I. E. E.* 1907, vol. 40, p. 7, and *Electrician* 1907, vol. 60, p. 160) said that when a dielectric under stress breaks down, a disruptive discharge ensues only when the effect of this partial breakdown is to increase the electric stress on the remaining portion. He also pointed out that in a composite dielectric subjected to alternating pressures, the voltages across the layers are usually out of phase with one another, and therefore that across each layer may be greater than indicated only by the thickness of the layer.

Osborne, H. (Trans. A. I. E. E. 1910, vol. 29-2, p. 1553) gave revised form ulas for the design of graded cables. He also advanced the theory that solid heterogeneous dielectrics fail due to corona in the elements of lower specific capacity. This corona is assumed to be in the form of needle points.

Beaver, C. J. (*Jour. I. E. E.* 1914, vol. 53, p. 57) mentions disadvantages of graded insulations and claims that desired results could be better obtained by means of intersheaths, because (1) no chemical interactions, (2) easier to joint, (3) no electrical discontinuity, (4) could be tested layer by layer as manufactured, (5) much wider latitude in choice of potentials.

Clark, W. S. and Shanklin G. B. (Trans. A. I. E. E. 1919, vol. 38-1, p. 923) say that practically no advantage is gained by an attempt to grade with rubber, varnished cambric and impregnated paper because the maximum allowable working stresses in these materials are inversely as their specific capacities. They claim that it is better to have the insulation a homogeneous compact mass of impregnated paper.

VIII. Miscellaneous Data

Rheins, G. (*Comptes Rendus*, 1900, vol. 131, p. 505) says that the metal of cables penetrates the insulation and destroys its insulating properties. He said that after 20 years, guttapercha insulation will show copper in its outer layers, whereas with impregnated paper only a few layers were penetrated in four years. (No other experimenters report this phenomenon).

O'Gorman, M. (*Jour. I. E. E.* 1901, vol. 30, p. 608) called attention to the effect of putting in series two elements of insulation having different specific capacities. He showed that the potential gradient is altered, the material of lower specific capacity carrying the greater part of the total potential drop across the two elements. (This fact seems to have been known to others at an earlier date.)

Newbury, F. J. (Cited by Perrine, Trans. A. I. E. E. 1902, vol. 19, p. 1067) said that in his experiments with fiber cables he could increase the dielectric strength of the cable up to a certain point, by increasing the thickness of insulation; beyond that point the cable seems to breakdown at almost the same potential, irrespective of increase in thickness.

Langsdorf, A. S. (*Elec. World* 1908, vol. 52, p. 942) reported tests on various insulating materials at frequencies from 30 to 110, that seemed to indicate that if the applied e. m. f. is above a certain critical value, breakdown occurs after a definite number of repetitions of the electrostatic stress.

Thornton, W. M. (*Phil. Mag.* 1910, vol. 19, p. 390) showed that the electrical movement in a dielectric, when isolated in the field, is entirely confined to the molecule and is therefore neither metallic nor electrolytic in type, but is a continued displacement of the atomic charges to a greater degree of separation.

Petersen, W. (*Archiv. fur Elektrotechnik* 1912, vol. 1, p. 28) showed that the refraction of lines of forces at the junction of two particles of different specific capacity in a dielectric may lead to an increase of dielectric stress.

Holttum, W. (Abstracted from a report to I. E. E. in *Electrician* 1913, vol. 71, p. 640) made tests on the relative dielectric strengths of ebonite for instantaneous and prolonged 50-cycle voltages and found that for stresses lasting a tenth of a second, the strength is only 25 per cent greater than for long continued stresses.

Lichtenstein, L. (*E. T. Z.* 1917, vol. 33, p. 1179) says that the progress in the use of thin walls of insulation for high voltages is not due to a lower standard of safety in working, but to improved chemical, physical and mechanical processes of manufacture. He says that probably at very high test pressures an excess of 25 or 50 per cent over the working pressure ought to suffice.

Butman, C. A. (*Elec. World* 1918, vol. 71, p. 812) showed that the specific capacity of a heterogeneous combination, such as of fullerboards soaked in oil, separated by three layers of paraffin, may be greater than that of either component alone. Thus, combination = 4.25, fullerboard = 3.32, paraffin = 3.69.

Fernie, F. (*Electrician* Oct. 10, 1919, p. 416) pointed out the superior dielectric strength of oil around small as compared with large conductors.

Zeleny, J. (*Phys. Review* 1920, vol. 16, p. 102) explained the added dielectric strength of an ionizable dielectric in contact with a small electrode as being due to the high potential gradient at the surface of the electrode as compared with that a short distance away, the velocity of the ions consequently dropping below the value necessary for ionization by collision, when they have travelled a short distance from the electrode.

Fernie, F. (*Beama*, Sept. 1921, p. 244) suggested that the stress which determines the failure of a cable is the minimum stress not the maximum.

Flight, W. S. (*Journal I. E. E.* 1922, vol. 60, p. 218) gives data on the effect of heat on the electric strength of paper, micarta, varnished cloth and other materials. He showed that the electric strength of varnished cloth is about 42 per cent less at 100 deg. cent. than at 30 deg. cent., that of oil saturated paper, about 27 per cent less.

Acknowledgment is made of the assistance given by the following Institute members who were so kind as to assist the subcommittee in the preparation of this summarized history: Messrs. R. W. Atkinson, F. W. Peek, C. E. Skinner, D. M. Simons and F. A. Westbrook. The Subcommittee on Wires and Cables appreciates the incompleteness of the summary, and has made but little effort to settle questions of priority in discovery. It is hoped that the discussion will correct whatever deficiencies may exist.

Discussion

For discussion on this paper see page 611.

Dielectric Losses and Stresses in Relation to Cable Failures

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Review of the Subject.—*When transmission cables were first operated at potentials exceeding about 7500 volts, it was noted that cable failures occurred in service with loads materially below those which had theretofore been found to be permissible with low-voltage cables, and this reduction in carrying capacity increased with increase of the normal working potential. For example the author has previously reported that No. 0 A. W. G. four conductor cables operating on a four-wire three-phase system with a maximum normal potential of about 4000 volts between phases carry 200 amperes on each of three conductors without damage due to the overheating, whereas a 250,000-cir. mil cable operated at 20,000 volts was found to have excessive burn-outs if the load exceeded 175 amperes per conductor.*

For a number of years it has been recognized that this reduction in carrying capacity of high-voltage cables was due to the dielectric losses and a number of papers have been presented to the Institute on this subject. A temperature survey of the 20-kv. cable above mentioned showed that nearly all of the burn-outs occurred in a portion of the conduit near the substation, which conduit contained a large number of heavily loaded cables, and in which the temperature was 10 deg. to 15 deg. cent. higher than the rest of the conduit. This portion of the 20-kv. line was replaced over two years ago with cable having a low dielectric loss, since which time no further cable failures have occurred.

The method of analysis first suggested by Bang and Louis and later extended by Clark and Shanklin was applied to this particular case, and the carrying capacity for the cable as determined in this manner was found to agree closely with the results of experience. The method was therefore extended so as to determine the law connecting the size of conductor, the dielectric loss and the carrying capacity. Curves and charts are presented showing the carrying capacity of all sizes of three-conductor cables above 100,000 cir. mils and of the entire commerical range of dielectric losses. These results were then compared with the operating records of a transmission system having cables ranging in size from No. 00 A. W. G. to 500,000 cir. mils and with operating voltages of 9, 12, 20 and 22 kv. The results of this comparison appear to indicate that practically all failures on these transmission lines, which were not due to external damage to the lead sheath, were due to the cables being loaded beyond their safe carrying capacity, and that the dielectric losses had not been given proper consideration in determining the carrying capacity of these cables.

During the year 1921 the number of cable failures on the 20,000-volt lines was about one per hundred miles. This was about the same as the record on the 9000-volt cables, and this result leads to the conclusion that when the transmission cables are operated at safe loads, in the determination of which dielectric losses have been given proper consideration, the resulting failures are of the order of one per hundred miles per year. This result indicates that very few of the cable failures which have occurred in the past are due to dielectric stresses and that most of the failures occur due to the reduction in dielectric strength caused by the heating of the cables above their critical temperature.

Foreign cable manufacturers and operating engineers have apparently appreciated the reduction in carrying capacity due to dielectric losses as they ordinarily limit their maximum conductor temperature to a point well below the critical temperature as determined by these investigations. Their publications also appear to indicate that they fully appreciate that the quality of the insulation is of prime importance and that increased security cannot be obtained by increasing the thickness of insulation without improving the quality. The tests on cables made at the factory indicate that with the thicknesses of insulation that are commonly used in this country, and with the insulation of the first quality, the cable will pass the test required by the Standards of the A. I. E. E. with a wide margin of safety.

Dielectric strength tests made on foreign cables and reported in the technical press indicate that the dielectric strength is generally materially above the corresponding figures obtained from tests on cables made in this country by a number of leading manufacturers. Apparently some material reductions in the thicknesses of insulation now used in this country for the transmission voltages can be made if the insulation is of first quality and has a low dielectric loss.

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INTRODUCTORY

DURING the past few years a number of papers concerning dielectric losses of impregnated paper insulation has been presented to the Institute and has contributed interesting and valuable information to our knowledge of this subject. As this knowledge increased, it has been apparent to some engineers that many of our transmission cable burnouts were due to the dielectric losses and the resultant heating and not primarily to the dielectric stresses. In the past, engineers in charge of the operation of transmission cables have repeatedly stated that transmission cables did not burn out from overload, and apparently based this statement on their experience with the carrying capacity of low-voltage cables. It now appears that these statements were in error, and that in making these statements, the engineers did not appreciate the extent to which the carrying capacity was limited by the dielectric losses. If the present symposium, of which this paper is a part, will do something toward clarifying our ideas on the relation of dielectric losses, dielectric stresses and temperature of the insulation to cable failures, it will have served a very useful purpose.

Presented at the A. I. E. E. Annual Convention, Niagara Falls, Ontario, June 26-30, 1922.

Data on Cable Failures

In order to secure some data which might assist in reaching proper conclusions on this subject, the records of the transmission line of the Commonwealth Edison Company for the past eighteen years have been compiled and are shown in Figs. 1, 2 and 3. In preparing these records, all failures caused by external injury to the lead sheath or by lightning, or failures on test, and all joint troubles have been eliminated so as to leave only failures of the cables which occurred in service. The amount of transmission line in service throughout this period is shown in Fig. 4.

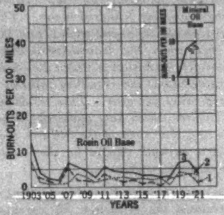

Fig. 1—Record of 9000-Volt Transmission Cable Failures
On system of Commonwealth Edison Company.
Curve 1—Internal troubles.
Curve 2—External damage.
Curve 3—Total.
Troubles due to lightning; failures on tests and joint troubles excluded.

Previous to 1919 all of the cables on this system had the paper insulation impregnated with a rosin oil compound. Beginning with that year, the cables have been purchased under specifications which included a dielectric loss guarantee, and in each succeeding year there has been some reduction in these guarantees. As a result, this record includes transmission cables ranging in size from No. 00 A. W. G. to 500,000 cir. mils and having dielectric losses ranging from about 0.5 to 15 watts per foot or more when measured at 85 deg. cent. at their normal operating voltages of 9, 12, 20 and 22 kv. It would be confusing to show the dielectric loss curves in watts per foot for this large range of sizes, as the losses vary with the size of the conductor. It will be more illuminating to show the range of power factors of the dielectric loss for the various kinds of cable, and an assortment of such curves is shown in Figs. 5 and 6.

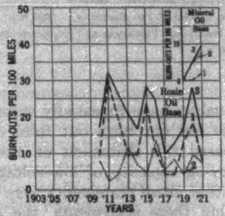

Fig. 2—Record of 12,000-Volt Transmission Cable Failures
Curves 1, 2 and 3, same designations as Fig. 1.

In order to analyze the operating results for the purpose of determining which, if any, of the cable failures have been due to dielectric losses, it is necessary to devise some method of rating the cables, that is, a method of determining their carrying capacity which will take into consideration the dielectric losses as well as the copper losses. Such a method was suggested by Bang and Louis in their Institute paper on Dielectric Losses, presented in June, 1917, and further developed by Clark and Shanklin in their paper on Single-Conductor High-Tension Cable, presented to the Institute in June, 1919. The application of the method may be best understood by its application to a specific example.

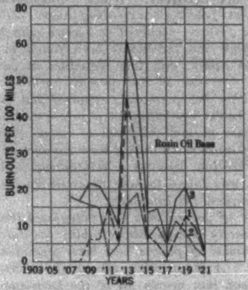

Fig. 3—Record of 20,000-Volt Transmission Cable Failures
Curves 1, 2 and 3, same designations as Fig. 1.

In March, 1917 there was placed in service a 250,000-cir. mil three-conductor 22,000-volt transmission line, No. 3801, from a suburban generating station into one of the outlying substations. The 4000 feet of this cable next adjacent to the substation was in a heavily loaded conduit, and repeated burn-outs occurred in this section. A temperature profile of this conduit taken by a recording thermometer in one of the vacant

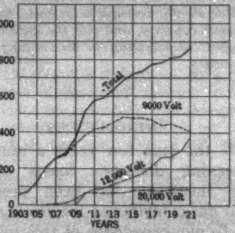

Fig. 4—Amount of Underground Transmission Cable in Service, Commonwealth Edison Company

ducts is shown in Fig. 7. A sample of this cable was tested for dielectric loss, and the results are shown in Fig. 8. In the hope of reducing the number of failures in this cable, the 4000 feet in the heavily loaded conduit was replaced with cable having a low dielectric loss as shown in Fig. 8. In the same figure is also shown the Clark and Shanklin line for average duct radiation which was obtained as the average of a large number of observations, and shows for each temperature the number of watts that can be radiated from the cable in one duct. In order that the temperature of the cable may be constant, the losses in the cable must equal the amount of heat radiated. With a curve showing the variation of dielectric loss with temperature to start with, we can for any temperature subtract the dielectric losses from the total radiation and secure the copper losses. From the latter figure, the current in the cable can be readily calculated. The results of such calculations for the old and the new cable are shown by curves in Fig. 8.

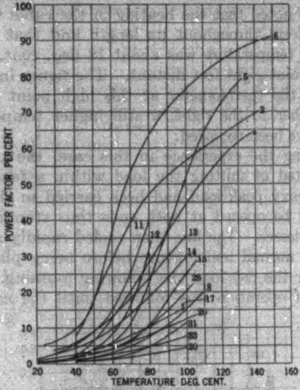

Fig. 5—Dielectric Loss Curves of 12,000-Volt Cables

The highest power factors are from cables impregnated with rosin oil compounds. The lowest losses are from cables impregnated with a mineral oil compound. The intermediate curves are from cables with various mixtures of the two compounds.

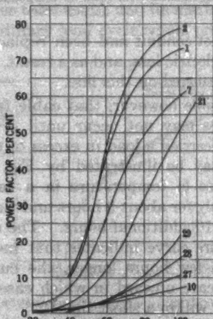

Fig. 6—Data Similar to Fig. 5 for 20,000-Volt Cables

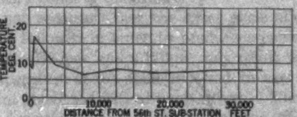

Fig. 7—Temperature Profile in Vacant Ducts Along Line No. 3801

Taken about April 1, 1922.

The temperature near the substation was lower at this time than at the time of the line failure described in the text due to several loaded cables having been removed from the conduit line, thus reducing the total losses in conduit about 15 or 20 per cent.

A chart from the recording ammeter on this line is shown in Fig. 9. This chart shows a normal load of about 150 amperes on the line up to about 5:20 p. m. at which time, owing to some trouble in other portions of the system, the load was increased to about 225 amperes for about an hour and three-quarters. As it was known that this line would not carry this load continuously, the load was reduced about 7:15 p. m. to what was considered a normal load for the line, and this load was carried until about 11 p. m., when a further reduction occurred. The line burned out the following morning about 3:30 a. m.

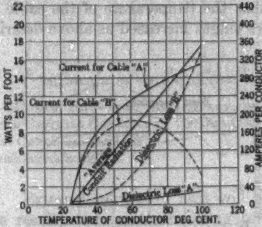

Fig. 8—Dielectric Loss Curves of Old Cable (*A*) and New Cable (*B*) on Line No. 3801 and Curves of Carrying Capacity as Calculated from Clark and Shanklin Line for Average Duct Radiation

These cables were 250,000-cir. mil., three-conductor with 19/64-in. paper around each conductor and 7/64-in. outer belt, for a normal working voltage of 22 kv. Old cable had round conductors, new cable has sector-shaped conductors.

Referring now to Fig. 8, it will be noted that the current of 225 amperes was materially above the critical current for this line. This means that the losses in the cable were greater than the radiation, so that the temperature rapidly increased. A peak load of 175 amperes had previously been found possible with this line if it did not continue very long and was sharply reduced thereafter. In this case, however the load of 175 amperes, which is about the critical load for this line, followed a peak load somewhat greater so that the temperature of the line having been materially increased by this heavy load, the total losses with 175 amperes were still above the radiation line, and the temperature continued to increase so that when the load was still further reduced to 100 amperes about midnight, the temperatures continued to increase until the line failed. These statements do not mean that the temperature of the cable throughout its entire length increased as above described, and in fact it is very probable that the temperature did not increase above normal except for a very small portion of the cable where the dielectric losses were higher than in the adjacent portions. This is demonstrated by Fig. 10 which shows the results of a laboratory test made on a piece of 250,000-cir. mil, three-conductor cable and is from the N. E. L. A. Underground Systems Committee report for 1913. This cable was operated with 225 amperes on each conductor, and with 12,000 volts between conductors. It will be noted that the heating in the cable was far from uniform throughout its length and that at one point the temperature was about 18 deg. cent. above another point eight feet distant. The figure indicates that had the thermometer at this high point been a little further to the right, a still higher temperature would have been recorded.

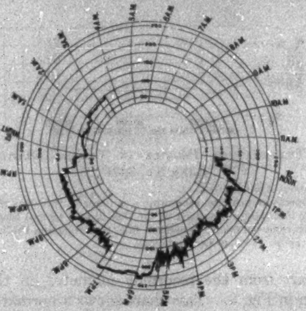

FIG. 9—RECORDING AMMETER CHART ON LINE NO. 3801

Showing a load in excess of the critical current in the evening, followed by failure about 3:30 the following morning, October 28, 1919.

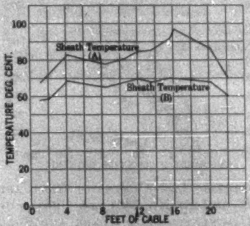

FIG. 10—LABORATORY HEAT TEST ON 250,000-CIR. MIL THREE-CONDUCTOR CABLE

With 6/32-in. insulation around each conductor and 4/32-in. outer belt paper insulation impregnated with rosin oilcompound. Reproduced from Report of Underground Systems Committee, National Electric Light Association, 1913.

A. Cable operated with 225 amperes at 12,000 volts.

B. 225 amperes, 0 volts. Temperatures taken by thermometers.

Following the experience in this case, the practise was adopted of shifting the load within a few hours after a heavy peak load had been carried so that the line could be opened at both ends thus stopping the dielectric losses. The line then cooled rapidly so that it was at normal temperature before being placed in service for the day load the following morning. This method of operation was followed until the cable in the 4000 feet of hot conduit had been replaced by the cable with low dielectric loss, and as a result, no further burn-outs have occurred on this line.

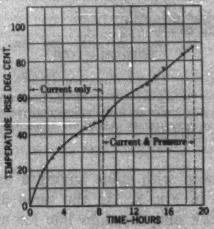

FIG. 11—HEAT RUN ON NO. 00 THREE-CONDUCTOR CABLE

With 9/32-in. insulation around each conductor and 6/32-in. outer belt paper insulation, impregnated with rosin oil compound.

It is quite possible however, that cable failures due to dielectric losses may not occur until several days after the line has carried a load in excess of the critical current. This may be illustrated by Fig. 11 which shows the increase in temperature in a cable which carried current only for about 9 hours and then current and potential for 10 additional hours. The upper part of this temperature curve indicates that had the test been continued a few hours longer, the curve would have become concave upward in which case the cable would have failed within a short time.

If a cable carries a maximum load that is less than the critical current each day on an ordinary load cycle with a daily load factor of about 50 per cent, then the cable will cool to about the same minimum temperature each night. If the cable carried for an hour or two a peak load, that exceeds the critical current, the minimum temperature at the time of minimum load will be a little higher than the minimum which occurs in the ordinary cycle. Suppose, now, that the peak load exceeded the critical current for a sufficient time so that the minimum temperature following was, say, 15 deg. higher than normal. This would mean that the cable would start on its ordinary load cycle 15 deg. warmer than usual, and its maximum temperature with its ordinary load cycle would probably exceed the critical temperature on the following day. Under such circumstances, the maximum temperature would increase somewhat day after day, with the ordinary load cycle, and in a few days the increase would be sufficient so that the cable would not fall below the critical temperature even at the time of minimum load. Then a burn-out would follow in a comparatively few hours, as illustrated above on Line 3801. Many of the failures of cable due to dielectric losses have occurred in this manner several days after the unusual load or other abnormal temperature conditions which were the primary cause of the failure.

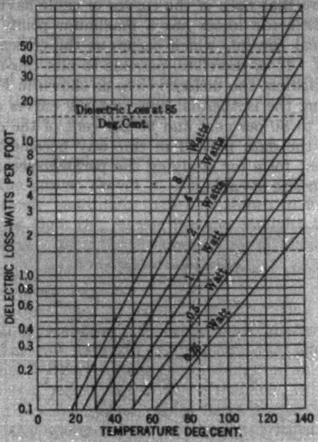

Fig. 12—Dielectric Loss Data Assumed for Purposes of Calculations

Based on a number of laboratory tests made for Commonwealth Edison Company.

In referring to these curves later, the lines will for convenience be designated by their loss at 85 deg. cent.

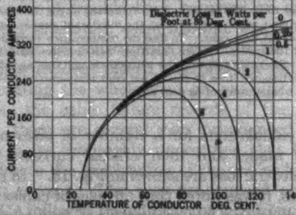

Fig. 13—Carrying Capacity of 250,000-Cir. Mil. Three-Conductor Cables

With dielectric losses as shown in Fig. 12 calculated from the Clark and Shanklin line for average duct radiation.

It is not necessary that the exact cycle above described be followed in order to produce a cable failure from dielectric loss, and a failure may result whenever the temperature of the cable is raised in any manner to a point above the critical temperature. The trouble may be due primarily not to the load on the cable which fails, but to heavy loads being carried on other cables in the same conduit so as to raise the ambient temperature. External sources of heat will also produce the same result, such as steam being turned into a sewer which is adjacent to the conduit line. Most companies operating high-voltage transmission lines have had experience with cable failures due to such causes. One company reports that it had to move transmission lines out of conduits which were laid close to the curb wall because of a bake oven located under the sidewalk and next to the curb wall. Other companies have reported difficulties due to the radiation losses from underground steam mains 15 to 20 feet distant.

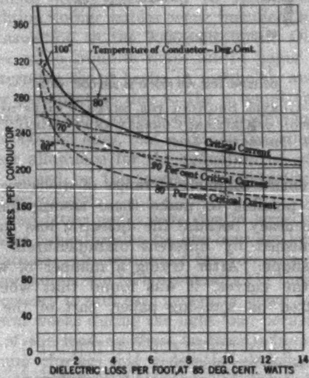

Fig. 14—Curve Showing the Effect of Dielectric Loss on the Critical Current of 250,000-Cir. Mil. Three-Conductor Cable

Plotted from curves in Fig. 13.

Extending This Method to Cover All Grades of Cable

By securing dielectric loss curves from cables covering a wide range of losses per foot, we can make similar calculations for a number of sizes and thus discover the manner in which dielectric losses affect the carrying capacity.

Figs. 5 and 6 give the dielectric loss results from a large number of cables, and with these and other similar data we can assume a number of dielectric loss curves over the entire commercial range of dielectric losses. It is not possible to make these assumptions with minute accuracy because the dielectric loss curves of cable furnished by different manufacturers are of different shape. After trying a number of ways of plotting the curves, it was found that when they were plotted on semi-log paper, part of the curves would be convex upward, part straight lines, and part convex downward. Accordingly the assumptions were made as shown in Fig. 12 and these assumptions fairly represent the average of the dielectric loss curves from cables over a wide range of quality as obtained from six different cable manufacturers.

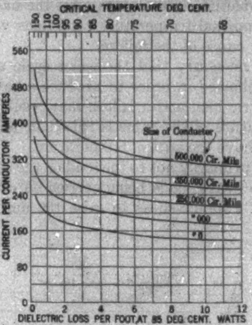

Fig. 15—Curves Showing for Several Sizes of Cable, the Variation of Critical Current and Critical Temperature with Dielectric Loss

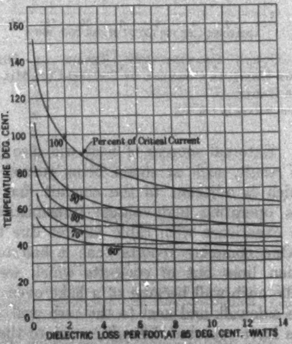

Fig. 16—Curves Showing Variation of Critical Temperatures with Dielectric Loss

For each of these assumed dielectric loss lines, calculations for 250,000-cir. mil, three-conductor cable were made as shown in Fig. 13. It will be noted in this figure that each of the curves of cable having the higher dielectric losses has a maximum point, called the critical current, which occurs at the critical temperature. It is, therefore, possible to plot this critical current against the dielectric loss as shown in Fig. 14. By adding the isothermal lines and the curves corresponding to 80 per cent and 90 per cent of the critical current, the data plotted in this way become a very convenient form for studying the performance of any particular size of cable.

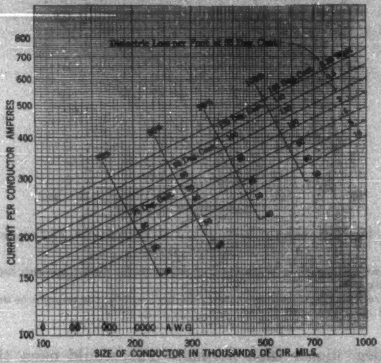

Fig. 17—Current-Carrying Capacity of Three-Conductor Lead-Covered Cables

With various dielectric losses and calculated from the Clark and Shanklin line for average duct radiation and from the dielectric loss lines shown in Fig. 12.

For a 250,000-cir. mil cable with four watts dielectric loss, the critical current is found to be 248 amperes. By following along the four-watt line to the 100 per cent scale, we find that the maximum copper temperature would be about 83 deg. cent. To find the temperature corresponding to 90 per cent of the critical current, multiply 248 amperes by 0.90, equals 223 amperes. Find this point on the 250,000-cir. mil line and then follow parallel to the diagonal lines to the 90 per cent temperature scale and get corresponding temperature of 62 deg. cent.

Similar calculations for a number of sizes of cable have been made, and their critical currents plotted against dielectric loss are shown in Fig. 15. In plotting these curves, it was noted that all sizes of cables having the same dielectric loss in watts per foot reach their critical current at the same temperature. It is therefore possible to add a temperature scale as shown in Fig. 15. From Fig. 13 and Fig. 15 it will be noted that a cable without dielectric loss has no critical current, and also that a cable with a low dielectric loss reaches its critical current at a temperature above the maximum permissible temperature for impregnated paper insulation.

In Fig. 16 is shown the curve of variation of the critical temperature with the dielectric loss. It would obviously be quite impossible to operate cables at their critical temperatures as determined by a dielectric loss test on a sample of cable, as such a test gives the average loss per foot for the entire sample and does not show the maximum dielectric loss at any point on the cable. Accordingly additional curves are included in Fig. 16 which show the temperatures that would be reached with several percentages of the critical current. From these curves it will be noted that a material reduction in the maximum temperature of the insulation can be made by a moderate reduction in the current below the critical current.

If the curves shown in Fig. 15 are transferred to logarithmic coordinate paper as shown in Fig. 17, it is found that the curves become straight lines and this permits using the calculations for all sizes of cable.

Fig. 17 shows the rating of all sizes of cables and in a full commercial range of dielectric losses as calculated by this method. By comparing this rating with the operating records of the system under discussion, and using as the ambient temperature the temperature obtained by a recording thermometer in an idle duct and about twenty feet from the manhole, we find that first, the transmission cables have in the past been frequently operated at or above their critical currents, and second, if the loads on the transmission cables are limited to about 90 per cent of the critical currents during the cooler months of the year and to about 80 per cent in the summertime, transmission line failures due to the dielectric losses will be practically eliminated.

Analysis of the Cable Failure Records

Referring now to the cable failure records of the 9000-volt cables, as shown in Fig. 1, this curve shows occasional peaks, and although the dielectric losses at 9000 volts are comparatively low, we know that some of these failures followed serious overloads. Some of these cases of trouble have occurred on one of three lines to a substation when one line was out of service on account of construction work in the substation, and some accident placed a second line out of service, thus putting the whole load on one line. In Fig. 3 showing the cable failure records of the 20,000-volt cables, there are several very pronounced peaks. It is now quite thoroughly understood that these peaks were due to the overloading of the cables beyond their critical current. The very pronounced peak in 1913 and 1914 followed the addition of a 24-hour load to the load previously carried on one group of lines which was reduced by the installation of an additional line in 1915. The pronounced peak in 1919 was due largely to the troubles on Line 3801 above mentioned. In 1921 however, after the low-loss cable had been substituted for the high-dielectric-loss cable in the hot conduit, and after a portion of the load on certain other lines had been transferred to the 12,000-volt, 60-cycle system, thus bringing the load on all 20,000-volt cables below their critical current, it is to be noted that the cable troubles dropped to about one per hundred miles per year or about the same as for the 9000-volt cables. This result indicates that practically all of our previous cable troubles on the 20,000-volt lines were dielectric loss failures and that when the load on these cables are kept within the limits at which the dielectric loss failures occur, then the remaining failures, that is, the failures due to dielectric stresses are quite insignificant.

The causes for the peaks in the 12,000-volt cable failures are more complicated. When the 12,000-volt system of tranmission to substations for alternating-current distribution was first installed to replace the motor-generators previously used for changing the frequency from 25 to 60 cycles, some of the old 9000-volt cables were transferred to 12,000-volt service. In addition, other cables were installed having the same insulation as the 9000-volt lines. Quite a few of these cable troubles were due to paper insulation being torn by sharp bends in manholes, and a larger number perhaps was due to the attempt to carry on these lines the same loads as had been previously carried on the 9000-volt lines, that is, due to the failure to make a proper allowance for the reduction in carrying capacity caused by the increase in dielectric losses at the higher voltage.

The two latter peaks were due in large part to the failures of cable forming tie line between large generating stations. On account of the necessity of cleaning and overhauling the turbo-generators in these stations, it is necessary to shut each generator down for a period of several weeks during the light-load period, and as a result of the load on these tie-lines is frequently at a maximum during this generator cleaning period in the summer-time. A number of these 12,000-volt cable failures also occurred in a conduit near the Northwest Station, where for a distance of about one block, two heavily loaded conduits were only a few feet apart, thus affording insufficient opportunity for the radiation of the heat. This trouble was stopped temporarily by cooling the conduit line with a stream of water applied intermittently. Later the 12,000-volt rosin-oil-impregnated cables were replaced with other cables having low dielectric losses.

Particular attention has to be paid to this question of conduit temperature, due to heavily loaded cables in the vicinity of stations and substations. Fig. 18 shows the temperature profiles of two conduit lines between the Fisk Street Station and the Calumet Station, in which there are several pronounced peaks along the route in the vicinity of substations. There is also a pronounced peak near the Fisk Street Station due to temporary storage of coal on the ground above the conduit line.

Another feature of interest in Fig. 2 is the record of cable failures due to external causes. These cables, as above mentioned, have the same insulation thickness as the 9000-volt cables. On a large system it would, at first thought, be reasonable to suppose that the percentage of failures due to external causes would be the same for all voltages of cable. Quite a few instances have occurred, however, where 9000-volt cables had their lead sheath damaged and no failure occurred, whereas under the same circumstances failures have occurred in the 12,000-volt cables. Several of these 12,000-volt failures assigned to external damage have occurred in cables which, upon being withdrawn for repairs after failure occurred, showed marks on the lead sheaths, indicating damage at the time of installation. A number of cases of damage to the lead sheath of 9000-volt cables have been found when the cables were being withdrawn for reinstallation at another location, and experience appears to indicate that had these cables been operated at 12,000 instead of 9000 volts, cable failures would have resulted. In one case, a 9000-volt cable, upon being withdrawn, was found to have the lead sheath burned off for a maximum length of two feet and a maximum width of about two inches, and the burn extended entirely through the outer belt insulation. This cable was installed in single-duct vitrified tile conduit and the damage had been caused by the failure of another cable in an adjacent duct about one year previously. The cable which was withdrawn had been in service throughout this period in the damaged condition and without developing any trouble at this location, although the cable was only six inches above the permanent ground water level.

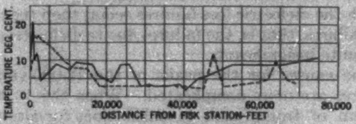

Fig. 18—Temperature Profiles Along Two Conduit Routes Between the Fisk Street Station and the Calumet Station

These several experiences appear to indicate that the 9000-volt cables have such an excess of insulation for the working voltage, that the increased dielectric stress due to these injuries to the lead sheath is not sufficient to cause a cable failure, although failures of 12,000-volt cable would generally occur under the same conditions.

Another contributing cause for the increased number of external damage failures of the 12,000-volt cables is that these lines have been installed more recently than the 9000-volt lines, and are therefore installed in ducts above the 9000-volt cables. Damages due to digging in the street would, therefore, be more likely to affect the 12,000-volt cables.

Results of Tests on Cables at the Factories

During the past three years the cables for addition to this transmission system have been purchased under specifications practically identical with those included in the report of the Underground Systems Committee of the N. E. L. A. for the year 1920, and the cables have been carefully tested at the factory in order to insure that they complied with the specifications in all respects. In addition, laboratory tests were made on impregnated paper from the cables to determine its quality.

Fig. 19 shows the results of a series of such tests that is quite representative and typical. In the folding endurance test the number of double folds of different samples varied from 45 to 13,000, while the other tests showed a much smaller variation.

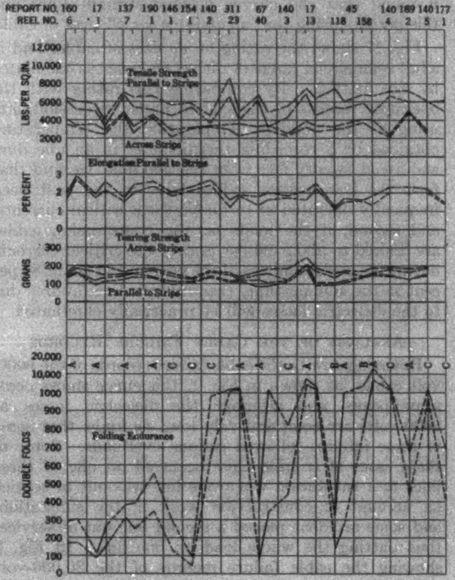

Fig. 19—Typical Tests on Physical Properties on Impregnated Paper Insulation Showing Variation in Quality of Paper

The two lines given for each series of tests represent the average and minimum values of results of tests on several samples of paper from each piece of cable. *A* denotes no tearing of paper in bending test in accordance with N. E. L. A. cable specifications; *B* denotes slight tearing, and *C* very bad tearing.

The tests made on these cables at the factory also showed a very large variation in the dielectric strength of the samples. In general, however, the cables passed the tests required by the Standards of the A. I. E. E. with a rather wide margin. As a result, the thickness of insulation during this period has been gradually reduced. For low-voltage cables the reduction in thickness of insulation has been about 50 per cent and for the high-voltage cables about 25 per cent to 35 per cent. Before making the last reduction, sample reels of cables with thin insulation were secured from several manufacturers and submitted to all the regular and special tests called for by the Standards of the A. I. E. E. and the N. E. L. A. cable specifications. The thicknesses as finally adopted are practically the same as the recommendations by the British Engineering Standards Association for voltages below 6000 and above this are practically the same as the thicknesses being used by some of the larger English companies. However, one of the latter companies has recently, on the basis of its own experience and on the advice of its consulting engineers, made a further reduction of 25 per cent in the thickness of insulation of cable for 20,000 volts normal operating pressure, the insulation being 300 mils between conductors and 210 mils to ground. The usual British practise calls for a maximum copper temperature of about 50 deg. cent. for transmission cables. Correspondence with English consulting engineers and cable manufacturers shows that their high-voltage cables have about the same dielectric losses as those furnished by the leading manufacturers in this country, that is, if measured at 85 deg. cent. the dielectric losses on their 20-kv. cables would be of the order of one watt per foot. By referring to Fig. 14, it will be noted that for a dielectric loss of one watt per foot and a copper temperature of 50 deg. there is a rather wide margin between the operating current and the critical current which might result in cable failures due to dielectric losses. Apparently therefore our British friends are of the opinion that as long as they continue to operate their cables under conditions which eliminate burn-outs caused by dielectric loss heating, then they can secure satisfactory operation with an insulation thickness less than two-thirds of what is considered necessary in this country.

RELATION BETWEEN INSULATION THICKNESS AND DIELECTRIC STRESSES

As a result of a thorough and persistent search, the author has reached the conclusion that there is in use in this country no scientific basis for determining the thickness of impregnated paper insulation on high-voltage cables. In the earlier days, when impregnated paper cables were first made, the manufacturers appear to have adopted the thicknesses of insulation previously used on cables with rubber insulation. No bending tests were made on these earlier cables, and the cables were installed with the same sharp bends that had previously been found permissible with rubber-insulated lead-covered cables. Our later knowledge indicates that many of these early failures must have been due to the tearing of the paper insulation caused by the bending during installation. Many of the older foremen and splicers who were raised on rubber insulated cables were quite firmly of the idea that it did not matter how sharp a bend or kink was made in the cable during its installation so long as these sharp bends and kinks were removed before leaving the cable in its final position.

As troubles from these earlier paper insulated cables occurred, the manufacturers and users, instead of making a determined effort to locate and remove the cause of trouble, adopted the simpler course of increasing the thickness of insulation, and until the last few years it does not seem to have occurred to anyone that they might have more insulation on their cables than necessary.

Several manufacturers in this country are making impregnated paper tubing consisting of paper impregnated with some insulating compound and then heat-treated so that the resulting material is very similar in its make-up to impregnated paper insulation used in lead-covered cables. One of these manufacturers in its circulars states that a quarter inch thickness of this material will stand a 100-kv. dielectric strength test, and further, that the dielectric strength varies with the square root of the thickness. From these data, curve *A* in Fig. 20 has been drawn.

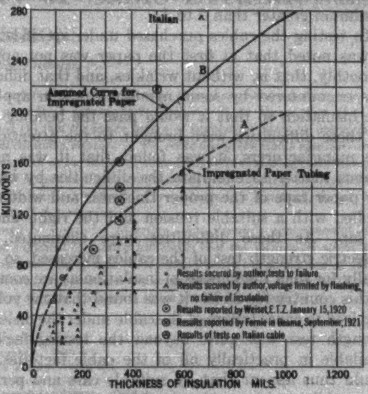

FIG. 20—DIELECTRIC STRENGTH TESTS ON IMPREGNATED PAPER INSULATION

A. Curve of dielectric strength guaranteed by one maker of impregnated paper tubing, in which the dielectric strength is proportional to the square root of the thickness.

B. Curve similar to *A* assumed by author from results of one test on 33-kv. cable.

The author in criticising the manufacturer of some cable with 600 mils insulation between conductors because the manufacturer had been satisfied with a dielectric strength test that was limited by cable bell trouble, attempted to make a dielectric strength test on a 15-foot sample, carrying the pressure to 212 kv.

between conductors. In this case also the pressure was limited by cable bell trouble and there was no failure of the cable within the lead sheath. Assuming that the dielectric strength of impregnated paper insulation also varies with the square root of the thickness, and using this particular point as our starting point, then we get the curve shown by *B* in Fig. 20. On the same sheet are also shown two points given by Weiset in the *E. T. Z.* for January 15, 1920, also six points given by Fernie in *Beama* for September, 1921, and also one figure giving results from an Italian cable, the latter data being obtained from private sources. On the same sheet are also shown the results of a large number of dielectric strength tests on various thicknesses of insulation made for the author on cables purchased in the last three years. For those thicknesses of insulation where a large number of tests are available, these results show a ratio of maximum to minimum greater than 2 to 1.

In testing the cables purchased under specifications, it was noted that at first the paper was not applied smoothly, that is, without wrinkles, and that difficulty was encountered by some manufacturers in applying the insulation so that it would pass the bending test. As these difficulties were brought to the attention of the manufacturers, it was found that it was not a serious matter to eliminate the difficulties by having the paper tape of the proper thickness and width and applied with a suitable tension and the right amount of lap. As these difficulties were eliminated, the dielectric strength test of the cables increased, so that finally for such thicknesses of insulation as are common in this country for 25 kv. it was found that the voltage required to cause failure of the cable under the dielectric strength test was quite beyond the testing facilities available in practically all of the cable factories. It would thus appear that by suitable care and perhaps some additional inspection in the factories, the American cable manufacturers should be able to make their cable of more uniform quality so that it would give results more nearly corresponding to the available data on foreign cables.

The American Engineering Standards Committee in gathering foreign specifications and standards for the use of its recently appointed Sectional Committee on Insulated Wires and Cables received an interesting communication from a Dutch Standards Committee which includes the following statement:

> The Association of Managers of Electric Central Stations have made an extensive study on high-tension cables, the results of which have been published. * * * * The most interesting result disclosed by this study is that, contrary to most opinions of today, it is not the thickness of insulation which gives the best guarantee for the reliability of the cable, but that the influence of the quality of the insulation material is very much greater.

How long will it be before American manufacturers will adopt the Dutch plan of increasing the reliability of their cables, not by increasing the thickness of insulation but by improving the quality?

The author recently had an interesting discussion with one of the technical executives of one of the larger manufacturing companies. This engineer had made some suggestions that certain changes should be made in the details of the manufacture of a certain line of electrical apparatus so as to improve the quality of the product. These changes were at first violently opposed by the superintendent of this factory, but after a thorough investigation the changes were put into effect. Then it was discovered that, in spite of the increased inspection and greater care in manufacture which resulted in a marked improvement in the quality, the improved manufacturing methods had brought about a reduction of about 5 per cent in the cost of the finished product. Is it not possible that a similar result might be secured in the manufacture of impregnated paper-insulated lead-covered cables?

CONCLUSIONS

1. After excluding the cable failures caused by lightning, external damage to the lead sheath and joint troubles, the remaining transmission cable failures on the system have been largely dielectric loss failures; that is, the cables have been loaded beyond their critical current as determined by their dielectric losses and cumulative heating, which followed, caused the cable failures.

2. The only cable failures that can be definitely ascribed to the dielectric stresses are a few that have been caused primarily by the tearing of the insulation due to sharp bends during installation.

3. Temperature readings in conduits are just as important as ammeter readings in the stations in determining the safe loads for transmission lines.

4. Some scheme of testing should be devised so that by means of some simple measurements it may be possible to determine the radiation constants of different portions of conduit lines in service and establish current ratings of transmission cables so as to eliminate the burn-outs due to overloads.

5. The thicknesses of insulation considered necessary in this country for transmission cables have been determined largely by experience with the cables in which the insulation was impregnated with a rosin oil compound and had high dielectric loss. If the Rules in the Standards of the A. I. E. E. are a sufficient criterion of the quality of the cable, then the thicknesses of insulation ordinarily used for transmission cables in this country can be very materially reduced, as cables with the present thicknesses of insulation with material and workmanship of the first quality, will pass the tests prescribed by the Standards of the A. I. E. E. with a wide margin frequently exceeding 100 per cent.

6. High-voltage cables having a low dielectric loss can be safely operated at temperatures materially higher than are possible with high-loss cables, due to the increase of the critical temperature with the reduction in dielectric losses.

7. The permissible operating temperature of high-dielectric-loss cables is limited by the critical temperature above which cumulative heating occurs. In low-loss cables the temperature is limited, as in low-voltage cables, by the temperature which the paper insulation will withstand without deterioration.

8. Until the proper method of calculating the limiting stresses of high-voltage cables and the limiting values for these stresses is determined, it will not be possible to design cables with the thickness of insulation properly proportioned to the working voltage.

9. If the dielectric losses of transmission cables are properly taken into consideration in fixing their carrying capacity, then for the thicknesses of insulation that are commonly used in this country, the percentage of burn-outs of the high-voltage cables should be no larger than for the lower transmission voltages and should not exceed one or two per hundred miles per year.

10. When the carrying capacity of a transmission cable with high dielectric loss is limited by the temperature of a short portion of the conduit in which it is installed, it may be found profitable to replace this portion of the cable with low-loss cable, and thus secure an increased carrying capacity for the entire line.

Discussion

For discussion on this paper see page 611.

On the Minimum Stress Theory of Cable Breakdowns

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Review of the Subject.—*For the rational and economical design of electric cables, it is important to know the relation bebetween the dimensions of the cable and its breakdown strength. Many different theories have been proposed in the past, such as the maximum stress theory, the average stress theory, Russell's theory, and Osborne's theory, all of them conflicting. Recently a new theory has been proposed by Fernie that the minimum stress, namely that at the sheath of a cable is the limit. It is the purpose of this paper to discuss Fernie's theory and data, inasmuch as it is so diametrically opposed to some of the earlier theories. It seems quite plausible that insulating materials have a specific breakdown stress. Fernie having discovered, as he states, that the minimum stresses were constant in his tests, feels forced to abandon this idea and attempts to explain his results in terms of a limiting value of stress at the sheath, namely the minimum value. An analysis of his test results, however, does not seem to justify him inasmuch as, although his minimum stresses were much more constant than the maximum stresses, they were by no means constant, and in fact, it could be claimed with almost equal justice that his test results vindicated the average stress theory.*

Since, however, Fernie's experimental minimum stresses present a certain degree of constancy, this phenomenon (which remains to be proved) is investigated further. It is shown that if it be assumed (1) *that the inner layers of insulation may be overstressed without complete rupture of the cable due to the stable equilibrium of the remainder of the insulation, and* (2) *that insulating materials have a critical breakdown gradient, a direct result of these two hypotheses is that the minimum stress at breakdown is a constant, though it is not in itself the criterion.*

It may be concluded therefore, that Fernie's experimental data are not sufficient to justify his claim that the minimum stress is a constant, and that if later tests should prove the constancy of minimum stress, this phenomenon could be explained otherwise than by assuming that the minimum stress itself is the limit.

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A KNOWLEDGE of the relation between the breakdown strength of cables and the size of conductor and insulation thickness is very important, if cables are to be rationally and economically designed. For instance, in a series of single-conductor cables all of the same insulation thickness, varying from small conductors to large conductors, will all these cables break down at the same voltage, or will those with small conductors break down at the highest voltage, or the lowest voltage? This fundamental question has not been adequately and convincingly answered even for the simplest case of all, the case of single-conductor cables. It is probable that it will never be possible to determine exactly the breakdown strength of a particular cable, due to the inherent lack of uniformity of insulating materials, but if a general law could be discovered, obtained by averaging the results of a great many samples, it would at least be possible to design cables with the same factor of safety. Any such law would also of course have to take into consideration the effect of time. A great many theories have been proposed, some of them quite conflicting, but there is a surprising lack of published experimental data on the subject. It has been claimed that the maximum stress in the insulation is the limit, that the average stress is the limit, as well as other intermediate theories. There has recently been proposed a radically different explanation. This theory is one offered by Fernie, who claims that the *minimum* stress or the stress at the sheath is the limit in the breakdown strength of single conductor cables[1]. Inasmuch as his theory is based on a greater amount of data than hitherto published and in view of the considerable

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[1] Fernie, "Insulating Materials," *Beama*, page 244, 1920.

interest evinced in this country in his conclusion, a discussion of his data and theory finds a proper place in this symposium. It is the purpose of the present article to discuss Fernie's data and to suggest a different explanation of his experimental results, and show that it is quite possible that the minimum stress may be constant and yet not in itself be the limit in the breakdown strength of cables.

For our purpose it will be assumed that insulating materials have a specific breakdown strength, which could be determined by puncture tests between parallel plate electrodes, inasmuch as in this case the stresses would be uniform throughout the insulation. Due to limits of space, no further discussion will be made of the many qualifications which should be made of this statement.

If an insulating material is contained between concentric cylindrical electrodes, such as the case of single-conductor cables, the stress, or gradient (or voltage per unit thickness) is by no means constant, but is a maximum at the conductor surface and a minimum at the sheath, and these two may be calculated by the following formulas:

$$G_{max} = \frac{E}{r \log_e R/r} \qquad (1)$$

$$G_{min} = \frac{E}{R \log_e R/r} \qquad (2)$$

where E is the voltage between the conductor and the sheath, R is the radius over the insulation, and r is the radius of the conductor.

One of the first theories of the breakdown strength of cables was that since every insulating material has a critical breakdown strength, which we may call G_0, as determined by the breakdown of layers of insulation between parallel plate electrodes, a single-conductor cable will break down as soon as this critical stress is exceeded in the insulation, which means that breakdown should occur when the maximum stress at the surface of the conductor is equal to the critical stress G_0. According to this maximum stress theory, if a series of cables of different dimensions and the same insulating material should be broken down, the calculated maximum stresses of all the cables at the breakdown voltage should be a constant and equal to the critical stress G_0. This would mean that for cables of a given insulation thickness, the larger the conductor, the higher would be the breakdown voltage.

The maximum stress theory of the breakdown strength of cable ignores one fundamental and well-known characteristic of the stresses in single-conductor cables, which may be briefly stated as follows. *For cables of a given outside diameter and given impressed voltage, the minimum value of the maximum stress at the surface of the conductor will exist when R/r equals ϵ, the base of the natural system of logarithms, or* 2.72. This characteristic may have an important bearing on the theory of the breakdown strength of cables. If a cable is of such proportions that R/r is greater than 2.72 and a high voltage is applied such that the inner layers of insulation tend to break down, this would result in virtually increasing the size of conductor, which would *diminish* the maximum stress in the insulation. The stresses in the remainder of the insulation would all be increased, but the maximum stress would be less than the maximum existing before the inner layers punctured, ane would therefore be less than the critical value. On the other hand, if R/r is equal to or less than 2.72, any puncturing of the inner layers of insulation will tend to *increase* the maximum stress. Cables may therefore be divided into two classes, which we shall call Class 1 in which R/r is greater than 2.72, and Class 2 in which R/r is equal to or less than 2.72. Russell[2] and Osborne[3] have developed different theories on the breakdown strength of cables, which take this feature into consideration, and which are well worth further study. Osborne takes issue with Russell's theory, but neither one publishes very much experimental data to prove his point. According to neither of these theories would the maximum stress or the minimum stress be constant at breakdown as calculated from the cable dimensions and the breakdown voltage.

FERNIE'S THEORY

Fernie, as stated before, has advanced a new theory. He performed a series of breakdown tests on cables of different sizes of conductor and insulation thicknesses, and has published his results, these results being probably the most complete experimental data on this subject on record. He states that it seems a very plausible theory that an insulating material should have a critical breakdown strength, and that therefore the cable should break down as soon as this value is exceeded in the cable insulation. If the maximum stress theory is true, the calulated maximum stresses at breakdown for the cables of a given insulating material should be constant. His results show that the maximum stresses are far from constant, varying in fact by over 200 per cent in one series, but he makes the remarkable statement that his minimum stresses were very closely constant. Based on his experimental data, he proposes that the minimum stress is itself the limit, and advances an interesting explanation of why this should be so, which explanation does not take the specific breakdown gradient into consideration.

FERNIE'S DATA

The comment has been made that Fernie's data are quite extensive, and it may be added that they are considerably more consistent than most of the data which have been published on this subject. It is by no means, however, intended to imply that they are sufficiently consistent to form in itself the basis of a new theory or to disprove some of the older theories. It is desired to discuss this phase of the matter briefly, and Fernie's experimental data are therefore shown in the following two tables. Table I refers to the data of his Table II, and Table II corresponds to the data of his Table III. R is the radius of the insulation, r is the conductor radius, and t is the insulation thickness.

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[2] "Dielectric Strength of Insulating Materials and the Grading of Cables," A. Russell, *Journal I. E. E.*, Vol. 40, page 6, 1907.

[3] "Potential Stresses in Dielectrics," H. S. Osborne, TRANSACTION, A. I. E. E., 1910, page 1553.

TABLE I.

R	r	t	R/r	$\log_{10} R/r$	Fernie's Breakdown Voltage in kv.	Maximum Stress G_{max}	Minimum Stress G_{min}	Average Stress G_{av}
mm.	mm.	mm.				kv/cm.	kv/cm.	kv/cm.
11.32	2.43	8.89	4.65	.6672	160.0	428	92.0	180
17.97	5.27	12.70	3.41	.5327	217.0	335	98.3	171
12.59	3.69	8.89	3.40	.5318	130.0	288	84.3	146
14.16	5.27	8.89	2.69	.4292	134.0	257	95.6	151
16.26	7.37	8.89	2.21	.3437	140.0	240	108.7	158
11.62	5.27	6.35	2.21	.3434	91.5	219	99.5	144
17.06	8.17	8.89	2.09	.3198	114.0	189	90.6	128
					Averages	280	95.6	154
					Deviations	+53%	+13.7	+17
						−32%	−11.7	−17
					Average Deviation	23.1	5.9	8.7

TABLE II.

7	2	5	3.50	.5441	54.25	216	61.8	109
9	3	6	3.00	.4771	69.0	209	69.7	115
11	4	7	2.75	.4393	65.3	161	58.6	93
13	5	8	2.60	.4150	83.9	175	67.5	105
16	6	10	2.67	.4257	94.2	160	60.1	94
					Averages	184	63.5	103
					Deviations	+17	+9.8	+11.6
						−13	−7.7	−9.7
					Average Deviation	12.3	6.4	7.6

Certain types of experiment lead to quite definite results which can be repeated at will. Tests on the breakdown strength of insulating materials are of a very different kind, and very great discrepancies usually occur between tests on supposedly similar samples, or even on different samples of the same piece of insulation. It is therefore necessary in breakdown tests to perform an enormous number of tests in order to average out the irregularities. Fernie's experimental data are based on the average of a great many tests, but even this does not mean that the number was sufficient to establish a law. Probably the main cause of the difficulty in breakdown tests is the inherent lack of uniformity of insulating materials. Due to the essential difficulty of the problem, any set of experimental data must be examined very critically and consideration must be given not only to whether or not the data would tend to disprove one theory and prove another, but also to see if there are not other theories which might also apply with about the same amount of deviation from the observed results. It will be seen in Tables I and II that though Fernie's calculated minimum stresses present a certain constancy, they are by no means rigidly constant. Fernie makes no mention of either Russell's or Osborne's theories, nor of the average stress theory, and apparently had in mind only the maximum stress theory. The departures from constancy of his calculated maximum stresses are so much greater than those of his minimum stresses that he apparently felt justified in calling the latter constant. If those were the only alternatives, his results would probably be sufficient to establish his claim. In fact, it may be stated that his results give fairly strong evidence to disprove the maximum stress theory. The question, however, still remains as to whether or not his results are definite enough to establish a constant minimum stress theory as opposed to some of the other theories. In Tables I and II, are shown the calculated maximum, minimum (with some minor errors in his calculations corrected), and average stresses at the moment of breakdown, and also the maximum plus and minus, and average deviations from the average. It can be seen immediately that the deviations from constancy of his minimum stresses are only slightly less than those of the average stresses, and that in Table II, even the maximum stresses are not much less constant than the minimum stresses. It is believed therefore that Fernie's claim for constancy of minimum stress at breakdown is not justified by his own data, and, to epitomize, it could be claimed with almost equal justice that Fernie's data prove the constant average stress theory and also Osborne's theory. If considerable emphasis is placed upon the points obtained from the cables with small sizes of conductor given in Table I, Fernie's data give fairly strong evidence against the maximum stress theory, and would indicate that Russell's theory is not adequate, though the evidence is less pronounced in the latter case.

Even though Fernie's test results do not seem to be consistent enough to definitely claim that the minimum stress is constant and that the other theories are wrong, still it must be admitted that the deviations of minimum stress are somewhat smaller than the other deviations, and it is therefore worth while to consider his results further and see what conclusions could be drawn if a series of tests should definitely prove the minimum stress to be constant. The cables which would show the greatest difference in breakdown strength according to the different theories are those for the larger and smaller values of the ratio R/r. Fernie's entire range for this ratio is only from about 2.1 to 4.7. It seems unfortunate, therefore, that he did not use greater extremes in the dimensions of his cables in his tests, in spite of certain difficulties, since cables with large values of the ratio would so clearly differentiate between certain of the theories, and cables with small values of the ratio are more in accord with everyday practise.

OVERSTRESSED INSULATION

The maximum stress theory assumes that the cable will puncture as soon as the critical stress is exceeded in any part of the insulation. Russell's theory assumes that no part of the insulation can sustain more than the critical stress, and that as soon as this value is exceeded, the insulation will break down and become equivalent to a conductor; whether or not the entire cable will breakdown depends on the dimensions of the cable. The other theories of the breakdown strength of cables assume the possibility in some form or other of overstressed insulation. The constant average stress theory does so implicitly. Osborne's theory is based upon the conception that the critical stress may be surpassed in the insulation, but that this will lead to breakdown in certain weak points resulting in minute needle-like punctures extending outward from the conductor, which thereby relieves the stress in the remainder of this region of the insulation throughout which the stress will be constant and equal to the critical value.

The possibility of the existence of overstressed insulation is not a new thought. For instance we might quote Whitehead[4] as follows:

> There is no difficulty in the idea of a strain of dielectric material beyond the electrical elastic limit with no resulting structural breakdown and resulting conductivity. In a single-conductor cable, we may think of a string of molecules stretched radially along a line of electric force. When the interior portion of the insulation is overstressed, but the insulation as a whole unbroken, we may think of the component charges of a molecule in the stressed region as drawn apart, and a tendency on the part of opposite charges of two adjacent molecules to combine. If this tendency could take place along the whole line of force there would be combination throughout and resulting discharge. The phenomenon would then be similar to conduction in a metal. In the case as supposed, however, the outer portions of the insulation are not overstressed, consequently proceeding outward from the conductor along the line of force there comes a region where there is a molecule which is not overstressed, which therefore successfully resists the tendency of one of its charges to pass to the adjacent overstressed molecule. This restraining influence is therefore propagated backward toward the center and serves to keep the overstressed portion from breaking down entirely. In this way the region of safe stress may be said to aid that in which this stress is exceeded.

According to Whitehead's conception a certain critical value of stress is required to draw apart the component charges of a molcule. It seems reasonable to assume therefore, that this critical value of stress will be all that would be required in the inner layers in order to hold the charges in this physical condition. This would mean that the stress in the overstressed region of the insulation would be a constant and equal to the critical stress, and that the overstressed region of insulation would not maintain its proportional share of the voltage, but would consume only a sufficient amount of the total voltage to hold the entire overstressed region at the critical value of stress. This would lead to a theory of the breakdown strength of cables mathematically equivalent to Osborne's theory though physically different. It is interesting to note that there is no critical point, or critical radius such as occurs in Russell's theory. That is, if a certain amount of the inner layers of insulation which would tend to be overstressed are held at constant value of stress equal to the critical value, any tendency to puncture the layer of insulation immediately adjacent to the outer layer of overstressed insulation would result in diminishing the stress in the succeeding layers to a value below the critical value. In other words, the equilibrium is stable, and there is no tendency for complete breakdown of the cable according to this theory until the voltage is raised to such a point that *all* the insulation is subjected to the constant stress equal to the critical value. According to this theory, then, if a series of cables is broken down, the *average stress* in the insulation as calculated from the cable dimensions would be a constant equal to the critical breakdown strength of the insulation. This discussion, therefore, is merely an interpretation of the average stress theory, and it might be repeated that Fernie's data could with almost equal justice be claimed to prove either the constant minimum stress theory or the constant average stress theory. This conception of the conditions in the insulation does not however lead to a constant minimum stress at breakdown, which must therefore be sought on other hypotheses.

PROPOSED EXPLANATION OF THE MINIMUM STRESS THEORY

A given set of experimental data may often be explained by entirely different physical theories. It is hard to believe that the critical breakdown strength of a cable as determined by parallel plates is not in some way the limiting feature, and Fernie's explanation does not seem to be very convincing. It is desired to show here, that, if it is a fact that the minimum stress at breakdown is a constant, this may be explained rationally in terms of the critical breakdown strength of the insulation combined with the conception of overstressed insulation, as well as by Fernie's theory, based on the "skin resistance" hypothesis, though the latter may of course have to be considered also.

To do this, it it will be assumed first that overstressed insulation may exist if the *remainder* of the insulation is in stable equilibrium, and secondly, that the overstressed insulation can support its proportional share of the voltage; in other words, that the distribution of potential throughout the cable will not be affected by the fact that certain inner layers are stressed above the critical value. The case of a cable of Class 1 (R/r greater than 2.72) will be considered. Let us imagine that the voltage on the cable is raised until the critical gradient is reached across the layer of insulation next to the conductor surface. If this layer should break down, the result would be a virtual increase in the size of conductor diameter, which would mean that the stress on the next layer of insulation, though increased above its previous value, would still be less than the critical value. The equilibrium of the cable as a whole may therefore be considered stable, and according to this theory, it is assumed that the breakdown does *not* take place in the inner layer due to the stable equilibrium of the whole cable. This is the distinction between this theory and Russell's theory. Russell assumes that actual breakdown and carbonization of overstressed layers take place. Here it is assumed that no action takes place but that the layers are overstressed due to the equilibrium of the whole system. Let us assume that the voltage is raised still higher. The inner layers of insulation will be stressed above the critical value, the maximum of course being at the conductor surface, and the critical stress will exist at a certain distance, x, from the center of the conductor. Having assumed the possibility of overstressed insulation, our attention must be directed upon the equilibrium of the remainder of the insulation, in other words between the region of radius x, where the critical stress G_0 exists, and the lead sheath. If R/x is greater than 2.72, any tendency for the critical gradient to puncture the layer at x would result in a stress upon the next layer which would be less than the critical gradient, and, as before, the equilibrium will be stable. On the other hand, if R/x is equal to or greater than 2.72, puncturing of the layer at which the critical gradient G_0 exists, would result in a stress upon the next layer higher than the critical value and we may consider the equilibrium as unstable. There is therefore apparently a critical point in the insulation, whose radius we shall call r' such that r' is equal to $R/2.72$. According to this theory, therefore, for cables of Class 1, as the voltage is raised continuously, the critical stress will first appear at the conductor surface and will then travel outward toward the sheath, all layers within this region being overstressed, the equilibrium of the cable as a whole being stable until the critical gradient reaches the raduis r', at which point it is assumed that breakdown will take place.

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[4] Whitehead, J. B., Discussion, TRANSACTIONS A. I. E. E., 1910, page 1582.

For cables of Class 2, in which R/r is equal to or less than 2.72, r' has no significance, and the cable would be in unstable equilibrium as soon as the critical gradient reaches the conductor surface. It would be expected, therefore, that breakdown would take place as soon as the critical gradient reaches the conductor surface, or in other words, the maximum stress theory would be applied to cables of Class 2, exactly as Russell did for cables of this class.

The results of this theory may now be examined mathematically. Let E' be the voltage between r' and R at the moment of breakdown. By formula (1) we may immediately express E' as follows:

$$E' = G_0\, r' \log_e R/r' \qquad (3)$$

and remembering that the natural logarithm of 2.72 is equal to unity and that r' equals $R/2.72$, we may state

$$E' = 0.368\, G_0\, R \qquad (4)$$

We may now solve for E, namely the actual breakdown voltage of the cable, inasmuch as the ratio of E to E' will be in inverse proportion to the relative capacities of the two sections. Therefore

$$E = \frac{\log R/r}{\log R/r'} \times E' = 0.368\, G_0\, R \log R/r \qquad (5)$$

The above equation gives the expression for the breakdown voltage of a cable in terms of critical stress and the dimensions of the cable according to the present suggested explanation.

The maximum stress at the moment of breakdown may now be obtained by substituting this value of E in equation (1) and we find that at the moment of breakdown

$$G_{max} = 0.368\, G_0 \times R/r \qquad (6)$$

The minimum stress at the moment of breakdown may also be obtained by substituting the value of E in equation (2) and we find that

$$G_{min} = 0.368\, G_0, \textit{ a constant} \qquad (7)$$

It will therefore be seen that a direct result of this theory is that for cables in which R/r is greater than 2.72, the minimum stress at breakdown will be a constant, as calculated from the actual cable dimensions and the breakdown voltage, and that this theory, based on the rational conception of a critical stress, will adequately explain Fernie's claim that the minimum stress is constant at breakdown.

It is desired to point out that for the case of cables of Class 1 there is a distinct difference between this suggested theory and Fernie's theory, in spite of the fact that according to both, the minimum stress will be constant. According to this theory, the cable punctures when the critical stress reaches the region whose radius is r', and a direct incidental result of this is that the minimum stress is constant. The critical stress G_0 at r' is in itself the limit, and not the minimum stress at the sheath. While these two theories are the same for cables of uniform dielectrics, they would lead to entirely different results in cables where different layers of insulation have different permittivities, such as in the case of graded cables. Only experimentation can determine which of these theories, if either, is correct. One test performed by Fernie throws some light on this point, inasmuch as he broke down two samples of cable, one uniform and one graded, and the results would tend to confirm his theory rather than the present one, and this test must therefore be taken into consideration. On the other hand, there is no indication that he broke down more than one sample of each type, which in itself would greatly discount the results of this one test.

While the theory outlined above explains the constancy of minimum stress for cables of Class 1 in terms of the critical gradient, it appears to be a rather difficult conception in one point at least, namely in the stability of the equilibrium of cables of Class 1 for values of the voltage intermediate between that given by equation (5) and the breakdown voltage according to Russell's theory. The present conception assumes the possibility of overstressed insulation and in determining the stability of the system places attention upon the understressed outer portions of the insulation, ignoring the inner, overstressed section. If investigation should be made as to what would happen to the cable as a whole, if the overstressed layers should give way, which seems a perfectly reasonable method of approach, it will be found that if the impressed voltage is higher than the breakdown voltage according to Russell's theory, and the overstressed layers should puncture, the stress at r' will be greater than the critical value, and the whole system would be in unstable equilibrium. If the applied voltage is less than Russell's breakdown voltage, the equilibrium will still be stable, and in fact, this method of approach would lead directly to Russell's theory, and would not lead to a constant minimum stress at breakdown as calculated from the cable dimensions. This would mean that there would be no distinction between Class 1 and Class 2 cables for a voltage higher than Russell's breakdown voltage, which leads to a difficulty, inasmuch as Fernie's data for the small sizes of conductor as shown in Table I give fairly strong evidence that the breakdown of these cables is higher than would be obtained according to Russell's theory. To explain this, it might be assumed that overstressed insulation (bearing its full share of the voltage) is possible and that breakdown will not take place until the critical stress reaches the sheath. This conception would lead to a constant minimum stress at breakdown for all classes of cable, the minimum stress being equal to the critical value. The difficulty is that conditions in Class 2 cables seem so essentially unstable as soon as the critical stress exists in the insulation that it is a little difficult to conceive of breakdown not taking place until the critical stress reaches the sheath. Also, this theory, as stated above, would mean that the minimum stress is equal to the critical stress, and Fernie's values of minimum stress seem too low for the critical stress of impregnated paper insulation. It does not seem necessary to adopt either of these theories, Fernie's theory, or possibly an entirely different theory, until definite experimental proof is obtained that the minimum stress at breakdown is constant.

EFFECT OF TIME

Up to the present, no mention has been made of the effect of time on breakdown voltage. This is a matter of the greatest importance, and it is believed that whatever law may be determined for the instantaneous breakdown strength of cables, the law would be quite different for cables in which the voltage is raised very slowly, for cables under long time test, or for cables in service. For instance, the present theory which involves the conception of overstressed insulation could not possibly hold in a cable of high dielectric loss under long time test, inasmuch as the heating of the overstressed layers would greatly change conditions, and would undoubtedly lead to breakdown in some cases from other causes. Quite aside, however, from the matter of the general heating of the cables due to dielectric losses, it is conceivable, and indeed probable, that there is a gradual deterioration of insulation which is overstressed, so that the limitation of working voltage of a single-conductor cable may well be the stress at or near the conductor surface, whereas the limitation of the voltage which may be sustained for short-time tests may be dependent upon some other function, such as the average stress, or even the minimum stress as suggested by Fernie.

CONCLUSIONS

It may be concluded that Fernie's data are not sufficient in themselves to justify his claim that the minimum stress is a constant at breakdown. The deviations of the minimum stresses from constancy are practically no greater than the deviations of average stress. There is, however, an indication that for the conditions of the tests and primarily their duration, the maximum stress theory is incorrect, though the data are inadequate to form the basis of a definite conclusion.

It may also be concluded that if a set of experiments should definitely indicate the constancy of minimum stress, even this would not mean that the minimum stress, or the stress at the sheath, is in itself the limit. The constancy of minimum stress may be explained in terms of the critical breakdown gradient of the insulation, together with the conception of overstressed insulation, and undoubtedly there are other methods of explanation.

The great present need in this problem seems to be experimental data. No attempt is made herein to go beyond experimental data which have already been published. The theory outlined herein is intended merely to show that Fernie's claim that the minimum stress is a constant is susceptible of another explanation, and no claim is of course made that the present theory is correct, because an essential of the theory is the constancy of the minimum stress for cables of Class 1, and this is not proved by the data published.

Discussion

For discussion on this paper see page 611.

Effects of the Composite Structure of Impregnated Paper Insulation on its Electric Properties

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The effect of composite structure upon the electric properties of dielectrics has been observed and theorized upon by various people, as mentioned in the Introduction. The present paper attempts to show a quantitative expression of power-factor and dielectric loss in terms of the resistivities and specific capacities of the elements of the insulation. It also shows the electrical function of the paper in impregnated paper insulation, and cites experiments which indicate that the electric failure of such insulation is due to ionic motion in the oil; the obvious deduction being that the voltage rating of cables should depend upon the degree to which ionic motion in the oil can be restrained.

CABLE dielectrics are composed of mixtures of various substances in which organic substances play the most important role.

Impregnated paper insulation consists principally of fibers of cellulose, surrounded by and filled with mineral oil. Rubber insulation consists of vulcanized rubber, hydrocarbons and various mineral substances. Varnished cambric insulation consists of cellulose fibers, air, oxidized oils and hydrocarbons. All of these components differ from one another in resistivity, specific capacity, and thermal characteristics and their juxtaposition leads to effects which influence the voltage at which they lose their insulating qualities.

DIELECTRIC LOSS

It is noted in the Committee's introduction that various physicists have explained residual charge and associated effects on the basis of heterogeneity of the dielectric and that Fleming and Dyke suggested that a heterogeneous dielectric might be represented by a pair of condensers in parallel, each condenser having a resistance in series with it as shown in Fig. 1. Wagner gave a quantitative exposition of the effect of heterogeneity upon residual charge and hinted that a similar method might be applied to the study of dielectric losses.

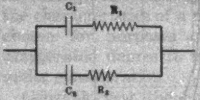

FIG. 1

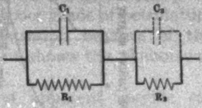

FIG. 2

Addenbrooke showed that Fleming's combination of parallel condensers leads to unsatisfactory conclusions. Following the logical development of Fleming's and Wagner's conceptions, the authors have tried the combination of condensers and resistances shown in Fig. 2.

If a leaky condenser, represented diagrammatically by C_1 and R_1 in Fig. 2 be placed in series with a resistance R_2 and an alternating potential impressed across the combination, the reactive as well as the active component of the current will, of course, be carried through the resistance R_2 and will cause a loss of energy therein. If the resistance R_2 be shunted by a condenser of capacity C_2 some of the current will be carried by that capacity (without energy loss) thereby reducing the energy loss in the resistance R_2. If the capacity C_2 be increased, a condition will be attained where the entire reactive component will be carried by the two condensers in series, and the active component by the resistances in series, no current then circulating across the connection. When the capacities and resistances are so proportioned, the energy loss in the combination will be a minimum for a given total resistance.

Some years ago, the authors noted a correspondence between residual charges and dielectric loss, those insulations having high residual charge invariably showing high dielectric loss. This afforded a confirmation of Wagner's suggestion and a theoretical analysis was made of the energy losses in a circuit consisting of two leaky condensers in series, for which see Appendix I.

The net result of this analysis was the following equation for the power factor of impregnated paper insulation. (See Appendix II)

$$\cos\theta = \frac{\dfrac{\rho_1}{a_1+1}+\dfrac{\rho_2}{a_2+1}}{\sqrt{\dfrac{\rho_1^2}{a_1+1}+\dfrac{\rho_2^2}{a_2+1}+\dfrac{2\,\rho_1\,\rho_2\,[1+\sqrt{a_1\,a_2}]}{(a_1+1)\,(a_2+1)}}}$$

Where ρ_1 = resistivity of impregnating compound ohm - cm.
ρ_2 = resistivity of cellulose fibres, ohm - cm.
K_1 = specific capacity of impregnating compound
K_2 = specific capacity of cellulose fibers
f = frequency of alternating e. m. f.

$$a_1 = \left(\frac{\rho_1\,K_1\,f}{18\times10^{11}}\right)^2$$

$$a_2 = \left(\frac{\rho_2\,K_2\,f}{18\times10^{11}}\right)^2$$

The specific capacity of petrolatum, the type of mineral oil generally used for this purpose, is about

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Presented at the A. I. E. E. Annual Convention, Niagara Falls, Ontario, June 26-30, 1922.

two and that of cellulose fibers about four, values which do not vary greatly with the grade or temperature. The resistivities of both substances vary enormously with the temperature, and in the case of petrolatum, to a considerable extent with the chemical composition. It is therefore of interest to see how the power factor varies with the resistivity of the petrolatum at a given temperature, say 85 deg. cent. assuming the other quantities to remain constant.

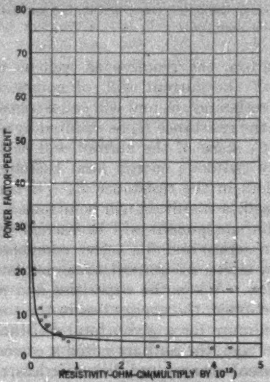

FIG. 3

Experimental data, represented by small circles, compared with theoretical curve.

Unfortunately a practical difficulty stood in the way—the determination of the resistivity of cellulose. The resistivity desired is not that of paper, nor even of paper fibers, but of the walls of the fibers. The fibers are about 7 mm. long and 0.02 mm. in diameter and they have a variable wall thickness of the order of 0.005 mm. It seemed almost impossible to make resistivity measurements upon such small specimens. Another difficulty was that the resistivity derived from measurement depends upon the time of electrification. As the research was primarily industrial, rather than purely scientific, it was decided to assume the equation to be correct, deduce the resistivity of the cellulose therefrom by tests based upon known values of specific capacity and oil resistivity. This was done for a one-minute electrification and at a temperature of 85 deg. cent. The resistivity of the cellulose at that temperature was found to be 0.07×10^{12} ohm-cm., a value consistent with tests by A. Campbell on other forms of cellulose.

Assuming this value, the power factor of the insulation was calculated for other oil resistivities. A graph of this relation is shown in Fig. 3.

Experiments were made both upon flat samples and upon cables and the results are shown by the circle-enclosed dots in Fig. 3. It will be observed that the experiments confirm the theory fairly well over a range of power factors from 2 per cent to 80 per cent.

This theory is not offered as a complete explanation of dielectric loss, but merely as an approximate working theory to guide designers. The phenomenon is undoubtedly far too complicated to be covered by any simple formula and a great deal of research work will be required before a complete explanation can be offered.

According to the above theory, the power factor should be inversely as the frequency when ρ_1 and ρ_2 are so great as to make the leakage current negligible. It should be independent of the frequency when ρ_1 and ρ_2 are so small as to virtually short circuit the capacities. For intermediate values, the power factor should decrease with increasing frequency according to the equation. The authors have not yet had an opportunity to make experimental checks of the effect of frequency.

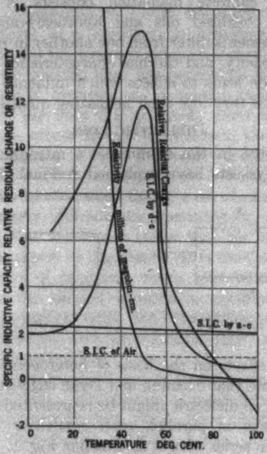

FIG. 4

The same general reasoning might be applied, although with greater difficulties, to the evaluation of dielectric loss in rubber compounds and varnished cambric insulation. It must be remembered, however, in applying the theory, it is assumed that no moisture is present, as a very small proportion will have a greater effect than even a fairly large reduction in the resistivity of one of the essential constituents. It is greatly to the credit of those concerned with manufacture that it is possible to obtain cables in which the moisture content is entirely negligible.

As dielectric loss in a well dried, well impregnated paper cable depends principally upon the conductivity of the oil, the loss must occur principally in the oil.

The work of Pungs, cited in the introduction to this symposium tends to show that conduction in oil is due to ionic travel rather than to mere ionic displacement. According to this theory, which is confirmed by tests cited below, a high-loss cable, *i. e.* one in which the "a-c. conductivity" is high, is liable to have the ions in its oil set into unduly rapid motion, a condition favorable to electric failure.

EVIDENCES OF FREE IONS

The test of any theory lies in its ability to explain phenomena. The test is especially satisfactory if a simple theory is found to explain a complicated series of phenomena. Regarded in this light, the theory that petrolatum normally contains free ions of both polarities is very satisfactory. The theory was effectively used by L. Malclès to explain the phenomena which occur when a petrolatum condenser is charged and discharged, using an electrometer to measure the charges. He showed that the behavior of such a condenser depends upon the viscosity of the petrolatum which, in turn, depends upon its temperature, and he explained this on the basis that the mobility of the ions is an inverse function of the viscosity.

Tests of capacity were made both by the d-c. and the a-c. methods, readings being taken over a range of temperature from 0 deg. to 100 deg. cent. and on a great number of specimens. The d-c. tests were made with a ballistic galvanometer, the petrolatum being in a cell, details of which are given in Appendix III. An example of the results is shown in Fig. 4 which gives the characteristics of a rather poor grade of petrolatum chosen for purposes of illustration because of the exaggerated degree to which it shows the phenomena under consideration.

Consider first the curve of apparent specific capacity, as measured by direct current.

When the condenser is charged, the negative ions are drawn toward the positive electrode and the positive ions, toward the negative electrode. When the condenser is discharged the ions diffuse from the electrodes, and redistribute themselves at random throughout the petrolatum at a rate depending on its fluidity. The current resulting from this ionic diffusion may or may not add itself to the true discharge current for the following reason: An appreciable interval of time elapses, in testing, between the end of the charge and the beginning of the discharge through the galvanometer circuit and the diffusion of the ions may occur in this interval. In this case the diffusion current would not be observable and the apparent capacity would equal the true capacity. This was found to occur at about 75 deg. cent.

With lower temperatures, the petrolatum being more viscous, the diffusion of ions is slower, until at a certain temperature it should last through the interval between the end of the charge and the beginning of the discharge. At lower temperatures, it should last longer, but should be weaker. Hence, at a certain temperature, the diffusion of ions should occur at such a speed as to make the apparent capacity a maximum. This temperature was found to be in the vicinity of the melting point, 50 deg. cent. In the case recorded in Fig. 4, the apparent capacity as measured with direct current, is about seven times the capacity as measured with alternating current. At yet lower temperatures the ionic diffusion is so slow, due to the viscosity of the petrolatum, that it should have little effect upon the apparent capacity. This condition was found at temperatures below 20 deg. cent.

If the petrolatum is sufficiently viscous the ionic diffusion which follows a discharge may continue long after the completion of the capacity test, and, if the condenser plates are kept insulated from one another, this redistribution of ions will result in residual charges on the plates. The residual charge one minute after the initial discharge was measured and the value at 80 deg. cent. arbitrarily taken as unity in order to show the relative values at different temperatures. These values are plotted in Fig. 4, and show that the residual charge reaches a maximum at a temperature slightly below the melting point. This would be expected from the theory of ionic diffusion because the residual charge should be most evident when the petrolatum is soft enough to permit diffusion but not so fluid as to allow this diffusion to be complete before the minute interval has elapsed.

Thus far we have considered only ions of molecular dimensions. Electrons will behave differently by virtue of their ability to travel through conductors. Electrons will be attracted to the positive electrode, but unlike the ions of molecular dimensions will not remain in the petrolatum. They will be drawn into the electrode and charging circuit and a corresponding number will appear on the negative electrode.

If the charging potential be removed, the electrons will diffuse through the petrolatum. If the electrodes be connected through a galvanometer, the moving electrons will set the electrons in the circuit moving in opposite direction to the discharge current, thereby reducing the apparent capacity and on later discharge, making the residual charge appear to be negative. These effects predominate only at such temperatures as correspond with very low viscosity, when the diffusion of molecular ions is so rapid as to produce no appreciable effect upon capacity measurements. In Fig. 4 this begins to occur at about 90 deg. cent.

The ionization theory of the residual charge of petrolatum does not explain the entire residual charge in a cable, this being due largely to the juxtaposition of the particles of oil and cellulose at whose surfaces charges are induced by virtue of their different specific capacities.

FUNCTION OF PAPER IN IMPREGNATED PAPER CABLES

An experiment was made to ascertain the effect upon the dielectric strength of petrolatum, of interposing various numbers of sheets of paper between testing electrodes. The experiment was made in an oil-testing cup having flat surfaced cylindrical electrodes ½ in. in diameter. The results are plotted as Curve *A* in Fig. 5, which shows clearly that in spite of the fact that after inserting the paper the oil was more highly stressed, due to the introduction of a dielectric of higher specific capacity, its dielectric strength increased as it was divided into thinner laminas by the introduction of more sheets of paper.

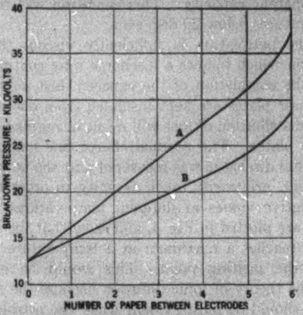

Fig. 5

If the paper be severely creased, and the crease viewed under a microscope, the line of the crease will be revealed as a hedge of fibres sticking out of the surface. In a cable, such projecting fibres will not act as barriers to ions trying to get through the paper, as they are loose and lie along, not across, the path of such ions. Hence we should expect badly creased paper, or paper with loose fibers, to be a less effective baffle to the ions and therefore to be less effective than smooth, tight paper in raising the dielectric strength of oil. An experiment similar to the last described was made with the only difference that badly creased paper was used. The results are shown by Curve *B* Fig. 5. It will be noted that both curves show a decided upward tendency, and further experiments, with different oils and papers have shown that this upward tendency continues as the number of papers increases, but experimental difficulties with the high voltages required to breakdown a wide gap, prevented obtaining a smooth curve for a much larger number of papers. Isolated experiments, however, indicate that the ratio of the breakdown voltages for uncreased and creased papers, keeps on increasing as the number of papers is increased, until it is at least two.

An interesting experiment was made with a radio frequency generator which showed in a very simple way the effect of serious creases upon the dielectric strength of impregnated paper. A plate of metal was connected to one pole of the generator and a movable wire connected to the other pole. The latter was held above the plate at such a distance that when about 17,000 volts were applied between wire and plate luminous white streamers extended between them. A sheet of oil-impregnated paper was then laid on the metal plate, with the result that the white streamers stopped immediately. When the wire was brought a little nearer the plate, faint purple streamers spread out from the wire, and flattened out over the paper. The crease in the paper was then brought within three cm. (horizontally) of the wire, the wire being one cm. above the paper. White streamers then spread from the wire to the plate through the crease as shown in Fig. 6.

Another sheet of impregnated paper with many creases was substituted for the first sheet and the wire moved slowly at right angles to the creases. Streamers jumped from crease to crease, never puncturing the uncreased paper.

A similar experiment made with unimpregnated paper, showed that the streamers were not attracted by the creases and proved that the harmful effect of creases is due to their effect upon the insulating properties of the oil rather than upon that of the paper itself.

The conclusion to be drawn from these experiments is that the electrical breakdown of impregnated paper is due to ionic motion in the oil, which is obstructed by the paper fibers.

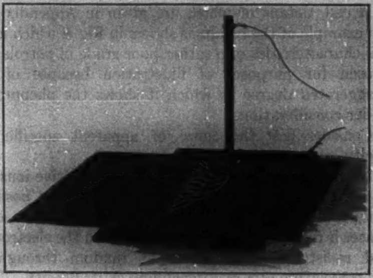

Fig. 6

Conclusions

Three sets of experiments have been cited and a theoretical explanation of each set has been given.

The first experiments indicate that when the power factor of impregnated paper insulation has been lowered as far as possible by the removal of air and moisture, there remains an element of power factor which depends upon the resistivity of the oil. This element is far too great to be explained on the basis of leakage current but may be explained as due to current which passes inductively through the capacity of the cellulose fibers and conductively through the oil.

The second experiments indicate that the oil used in impregnated paper insulation normally contains free ions in considerable quantities.

The third experiments indicate that the failure of impregnated paper insulation may be due to the establishment of streams of ions in the oil.

It would be logical to deduce from these considerations that in designing and using high-voltage cables particular care should be taken to impose every possible restraint upon ionic motion in the oil.

The practical means of accomplishing this are as follows, it being assumed that manufacturing processes will eliminate all air, vapor, and moisture:

1st. Use paper of a quality and thickness that will have the maximum baffling effect.

2nd. Apply the paper so that it will exert the maximum baffling effect.

3rd. Avoid sharp bends or other severe mechanical strains in manufacturing and installing.

4th. Use oil of a quality to make the dielectric loss fairly low.

Appendix I

THEORY OF ENERGY LOSS IN A PAIR OF LEAKY CONDENSERS IN SERIES

A pair of leaky condensers in series may be represented for purposes of calculation by a pair of perfect condensers in series, each condenser being shunted by a non-inductive resistor.

Consider a pair of perfect condensers having capacities c_1 and c_2 and a pair of resistors having resistances r_1 and r_2 arranged as in Fig. 2, and suppose a sinusoidal e. m. f. of E volts to be imposed between the terminals A and C.

Let
$$a_1 = (2\,\pi\,f\,r_1\,c_1)^2 \qquad (1)$$
$$a_2 = (2\,\pi\,f\,r_2\,c_2)^2 \qquad (2)$$

Then the cosines of the imperfection angles of the parts $A\,B$ and $B\,C$, will be as follows:

$$k_1 = \frac{1}{\sqrt{1/a_1 + 1}} \qquad (3)$$

$$k_2 = \frac{1}{\sqrt{1/a_2 + 1}} \qquad (4)$$

and the sines of the imperfection angles will be as follows:

$$s_1 = \frac{1}{\sqrt{a_1 + 1}} \qquad (5)$$

$$s_2 = \frac{1}{\sqrt{a_2 + 1}} \qquad (6)$$

Let i_1 and i_2 be the currents in r_1 and r_2 respectively and I_1 and I_2 the currents in c_1 and c_2 respectively. Then the total power loss will be:

$$W = i_1^2\,r_1 + i_2^2\,r_2 \qquad (7)$$

Let Z_1 and Z_2 be the impedances from A to B and B to C, respectively. Then

$$Z_1 = r_1\,s_1 \qquad (8)$$
$$Z_2 = r_2\,s_2 \qquad (9)$$

and the total impedance from A to C equals

$$\begin{aligned} Z &= \sqrt{(Z_1\,k_1 + Z_2\,k_2)^2 + (Z_1\,s_1 + Z_2\,s_2)^2} \\ &= \sqrt{Z_1^2 + Z_2^2 + 2\,Z_1\,Z_2\,(k_1\,k_2 + s_1\,s_2)} \end{aligned} \qquad (10)$$

Combining **8** and **9** with **10**

$$\begin{aligned} Z^2 &= r_1^2\,s_1^2 + r_2^2\,s_2^2 + 2\,r_1\,r_2\,s_1\,s_2\,(k_1\,k_2 \\ &\quad + s_1\,s_2) = \frac{r_1^2}{a_1 + 1} + \frac{r_2^2}{a_2 + 1} \\ &\quad + 2\,r_1\,r_2\,\frac{1 + \sqrt{a_1\,a_2}}{(a_1 + 1)\,(a_2 + 1)} \end{aligned} \qquad (11)$$

As the drop from A to B is the same in amount by either parallel path and as the drop from B to C is the same in amount by either parallel path

$$i_1\,r_1 = \frac{I_1}{2\,\pi\,f\,c_1} \text{ or } I_1 = i_1\,\sqrt{a_1} \qquad (12)$$

$$i_2\,r_2 = \frac{I_2}{2\,\pi\,f\,c_2} \text{ or } I_2 = i_2\,\sqrt{a_2} \qquad (13)$$

If I be the total current through the circuit

$$I = E/Z = \sqrt{I_1^2 + i_1^2} \qquad (14)$$
$$I = E/Z = \sqrt{I_2^2 + i_2^2} \qquad (15)$$

Combining **12** and **14**

$$E/Z = \sqrt{i_1^2\,(a_1 + 1)}$$

and combining **13** and **15**

$$E/Z = \sqrt{i_2^2\,(a_2 + 1)}$$

whence

$$i_1^2 = \frac{E^2}{Z^2\,(a_1 + 1)} \qquad (16)$$

$$i_2^2 = \frac{E^2}{Z^2\,(a_2 + 1)} \qquad (17)$$

Inserting the values from **16** and **17** in **7**

$$W = E^2\,\frac{\dfrac{r_1}{a_1 + 1} + \dfrac{r_2}{a_2 + 1}}{Z^2} \qquad (18)$$

Combining **18** with **11**

$$W = E^2\,\frac{\dfrac{r_1}{a_1 + 1} + \dfrac{r_2}{a_2 + 1}}{\dfrac{r_1^2}{a_1 + 1} + \dfrac{r_2^2}{a_2 + 1} + \dfrac{2\,r_1\,r_2\,(1 + \sqrt{a_1\,a_2})}{(a_1 + 1)\,(a_2 + 1)}} \qquad (19)$$

It is of interest to note that if $a_1 = a_2$ the above equation reduces to

$$W = \frac{E^2}{r_1 + r_2} \qquad (20)$$

indicating that the loss, in this case, is the ohmic loss due to leakage current only.

The power factor $\cos\,\theta$ may be derived as follows:

By definition

$$\text{Cos}\,\theta = \frac{W}{E\,I} = \frac{W\,Z}{E^2} \qquad (21)$$

Combining equations **18** and **21**

Cos θ =

$$\frac{\dfrac{r_1}{a_1+1} + \dfrac{r_2}{a_2+1}}{\sqrt{\dfrac{r_1^2}{a_1+1} + \dfrac{r_2^2}{a_2+1} + \dfrac{2\,r_1\,r_2\,(1+\sqrt{a_1\,a_2})}{(a_1+1)\,(a_2+1)}}} \qquad (22)$$

Appendix II

POWER FACTOR OF HETEROGENEOUS INSULATION

A non-homogeneous dielectric consists of a mixture of particles of different resistivities and specific capacities. When a potential difference is established across such a dielectric, it sets up both displacement and conduction currents. At the boundaries between particles of different resistivities and specific capacities, the current may change from a conduction to a displacement current, or vice versa, just as at the plates of a condenser, the current changes from a displacement current into a conduction current as it leaves the dielectric and enters the plates. The total $i^2\,r$ loss may therefore be due not only to the leakage current but also to local conduction currents generated in particles of the insulation by the displacement currents.

A homogeneous dielectric may be represented by a capacity shunted by a resistance. When alternating voltage is applied across such a dielectric, the only energy loss that occurs is the $i^2\,r$ loss due to that portion of the current which passes through the resistance and this is the same for direct as for alternating currents.

A non-homogeneous dielectric may be represented by two or more shunted capacities in series. In the case of a dielectric consisting of two elements, if one of these capacities is high and the shunted resistance of the other is low, most of the current will pass inductively through that capacity and conductively through that resistance causing a high ohmic loss in the latter. This loss constitutes the major part of the dielectric loss and can occur only with alternating current.

It was shown in Appendix I that the power factor of two leaky condensers in series may be represented by the following equation:

Cos θ =

$$\frac{\dfrac{r_1}{a_1+1} + \dfrac{r_2}{a_2+1}}{\sqrt{\dfrac{r_1^2}{a_1+1} + \dfrac{r_2^2}{a_2+1} + \dfrac{2\,r_1\,r_2\,(1+\sqrt{a_1\,a_2})}{(a_1+1)\,(a_2+1)}}} \qquad (22)$$

The quantities a_1 and a_2 in this equation each contains the product of the resistance and capacity of one of the elements of the dielectric. But this product may be expressed in terms of resistivity ρ_1 or ρ_2 and specific capacity K_1 or K_2 by the following well known relations:

$$\left\{\begin{aligned} r_1\,c_1 &= \frac{\rho_1\,K_1}{36\,\pi \times 10^{11}} \\ r_2\,c_2 &= \frac{\rho_2\,K_2}{36\,\pi \times 10^{11}} \end{aligned}\right. \qquad (23)$$

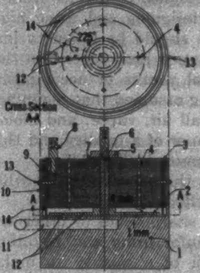

FIG. 7—ELECTROLYTIC CELL FOR LIQUID INSULATION

No	No Req.	Material	Description
1	1	Brass	Bowl 9.4 cm. in diameter with lip 9 mm. high & 2 mm. in thickness (see 11)
2	1	"	Circular plate 8 cm. dia. 2 mm. thick with collar 1.6 cm. dia. 4 mm. thick (see 12)
3	1	"	Cylinder 8.4 cm. inner dia. 1 mm. thick., axial length = 4 cm., with flap for binding post.
4	4	—	Holes bored through "9" parallel with axis, at radial distance of 5 cm. 2 mm. dia.
5	1	Brass	Nut to same thread as "6"
6	1	Steel	Pin 6 mm. dia. 5.2 cm. long threaded upper end to fit "5" & drilled & tapped to take "8"
7	1	Brass	Washer 3.5 cm. dia., center hole 6 mm. dia. 1 mm. thick.
8	2	"	Binding posts 1.25 cm. long & 6 mm. dia. (wire hole 2.5 mm. dia.)
9	1	Insul. Material	Circular block, axial length 3.8 cm. 8.4 cm. dia. (see 4)
10	1	"	Ring, axial length 4 cm. & 4 mm. thick with flange cut out bottom end 3 mm. deep to fit "1"
11	1	—	Thermometer hole bored 5.8 cm. deep & 8 mm. dia.
12	8	—	Holes bored through "2". 1 mm. dia. at radial distance of 1.5 cm. from center
"	16	—	Holes bored through "2". 1 mm. dia. at radial distance of 3 cm.
13	4	Brass	Screws. 1 cm. long
14	16	—	Vent holes. 1 mm. dia.

Inserting these values in equations (**1**) and (**2**):

$$\left\{\begin{aligned} a_1 &= \left(\frac{f\,\rho_1\,K_1}{18 \times 10^{11}}\right)^2 \\ a_2 &= \left(\frac{f\,\rho_2\,K_2}{18 \times 10^{11}}\right)^2 \end{aligned}\right. \qquad (24)$$

If, as is approximately the case in impregnated paper, the thickness of the two elements, paper and oil, averages about equal, the resistances r_1 and r_2 may be replaced by resistivities ρ_1 and ρ_2. Hence, equation (**22**) may be expressed as follows:

Cos θ =

$$\frac{\dfrac{\rho_1}{1+a_1} + \dfrac{\rho_2}{1+c_2}}{\sqrt{\dfrac{\rho_1^2}{1+a_1} + \dfrac{\rho_2^2}{1+a_2} + \dfrac{2\,\rho_1\,\rho_2\,(1+\sqrt{a_1\,a_2})}{(1+a_1)\,(1+a_2)}}} \qquad (25)$$

If ρ_1 and ρ_2 are as great as they are usually found to be, the *ones* may be omitted without appreciable error, the equation then reducing to the following simple form.

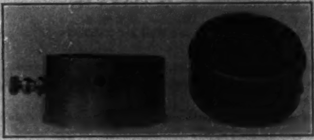

Fig. 8

$$\text{Cos } \theta = \frac{A_1^2/\rho_1 + A_2^2/\rho_2}{A_1 + A_2} \qquad (26)$$

Where $$A_1 = \frac{18 \times 10^{11}}{f K_1}$$

$$A_2 = \frac{18 \times 10^{11}}{f K_2}$$

Appendix III

CELL FOR RESISTANCE AND CAPACITY MEASUREMENTS

The resistivity of petrolatum was determined by measurements of a film 1 mm. thick and 8 cm. in diameter. The design of the cell, in which measurements were made, is shown in Fig. 7, and its appearance in Fig. 8.

The general arrangement of the testing circuit is shown in Fig. 9. With this apparatus the resistivity of an oil can be determined over a range of temperature from 30 deg. cent. to 105 deg. cent. in three-quarters of an hour.

The heating of the cell is accomplished by placing it on an electric hot-plate. With a reasonably sensitive galvanometer a sufficiently great deflection can be obtained to ensure an accuracy of 10 per cent. This may seem to be a large error, but the authors have known cases where different laboratories, using different types of cells, could not check such measurements within 50 per cent.

Capacity measurements were made with direct current by the ordinary ballistic galvanometer method, and with alternating current by a new method involving the use of a guard ring. The diagram of connections is shown in Fig. 10. C_1 is the cell connected in the Wheatstone bridge circuit. The resistance R_g is in series with the guard ring of the cell to prevent a serious arc in case the oil should fail under the application of voltage. The detector G is a Weibel electromagnet moving-coil galvanometer. The mutual inductance M, the resistance R and the capacity C are parts of the moving-coil circuit of the galvanometer and serve to stabilize the deflections and to produce critical damping. The shield circuit, R_3 and C_3, was adjusted by connecting the galvanometer to post A and varying R_3 until the galvanometer showed no deflection when the key K was reversed. After this adjustment had been made the bridge could then be accurately balanced by connecting the galvanometer to the post B and varying the resistance R_1.

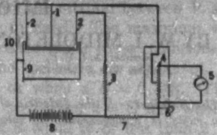

Fig. 9—Diagram of Connections—Resistivity of Oils

1. Upper electrode of resistivity cell.
2. Guard ring of resistivity cell.
3. Jagabi resistance 2000 ohms.
4. Ayrton galvanometer shunt.
5. Galvanometer.
6. Paraffine slab under Ayrton shunt.
7. Megohm.
8. Battery of dry cells.
9. Lower electrode, bowl of resistivity cell.
10. Connection for obtaining constant of galvanometer.

For measuring the specific capacity of oil, a substitution method was used. The first balance was obtained with only air in the cell and then a second balance with the oil in the cell. The ratio of R_1 obtained in the first balance to that obtained in the second balance, is the specific capacity of the oil.

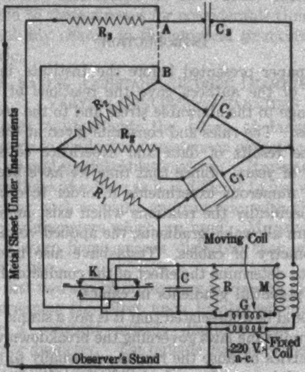

Fig. 10

To check the accuracy of the method, the capacity of the cell with air was measured by substituting for the cell a condenser of known value. The measured capacity was found to be 0.000099 microfarads as compared with 0.000098 microfarads calculated from the dimensions of the cell.

The specific capacity of an oil could be measured over a temperature range of 30 deg. to 105 deg. cent. in an hour with an accuracy of about 3 per cent.

Discussion

For discussion of this paper see page 611.

Potential Gradient In Cables

Discussion of the Logarithmic Formula, Its Modification and Effect of Internal Heat

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Review of the Subject.—*If the dielectric of a single-conductor concentric cable is homogeneous, the voltage gradient at any diameter x is given by*

$$\frac{d\,v}{d\,x} = \frac{0.368\ V}{x \log_{10} \dfrac{D}{d}}$$

where $\frac{d\,v}{d\,x}$ *is the voltage gradient or dielectric stress, V the voltage between conductor and sheath, D the diameter over the dielectric and d the diameter over the conductor.*

A complete discussion of the above formula is followed by considerable experimental data and curves accumulated from many breakdown tests.

Results of tests on cables with large ratios of dielectric diameter to conductor diameter are included and a modification of the above theoretical formula is discussed. The modified formula is checked by tests on a special cable which was constructed for this purpose.

A new relation between the rupturing gradient at the surface of the conductor and the ratio D/d is suggested and curves of experimental data given.

Breakdown tests on three-conductor cables are included and the calculated rupturing stresses compared with those for single-conductor cables.

Special cables were constructed so that measurements could be made of voltages between layers of insulation. From data obtained from these tests, curves are given showing the change in potential gradient as the internal heat of the cable is increased. Curves are given showing the effect of a change of temperature on the dielectric strength, the stresses and the factor of safety of cables.

A complete description is given of the low-capacitance electrostatic voltmeter used in the temperature-potential-gradient tests.

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INTRODUCTION

In a paper presented before the Institute in 1914[1] two of the authors gave the relations of testing voltage to the allowable stress and to the geometry of cables. The rules and constants given at that time were the results of data and experience covering a number of years. Since that time we have been conducting numerous experiments in order to determine more specifically the relations which exist among the maximum allowable gradients, the applied voltage and the geometry of cables. Tests have also been conducted to determine the effect of the conductor heating on the potential gradients in cables.

It should be appreciated that it is not a simple matter to determine the laws governing the breakdown voltage of dielectrics because the results are usually so erratic. The breakdown voltage for various sections cut from the most carefully made cable varies over wide limits even under the same conditions of test, owing to the fact that it is practically impossible to make homogeneous insulation. When a weak spot yields to the stress, more stress is immediately concentrated on the remaining layers, and the cable punctures. This action is cumulative and tends to produce erratic results, even under the best of conditions. The breakdown voltage is also a function of the rate of application of voltage, length of cable tested, etc. We have taken every precaution to prevent inconsistent results, by raising the potential at the same rate in every case, by using the same lengths of cable, and by taking the average of at least five readings for each test.

We are presenting the results obtained from numerous experiments and indicating the laws which breakdowns, etc., appear to follow in these tests. We do not claim that these laws are final, but on the contrary we feel that considerable more data must be obtained before any such laws can be accepted as final. In order to conduct a series of tests which will give satisfactory results, a large number of cables having the same dielectric, but with fixed outside diameters and variable conductor diameters, and also cables with fixed conductor diameters and variable outside diameters must be carefully made and tested. The fact that this involves considerable time and expense has prevented more data of this character being obtained.

If the dielectric of a single-conductor concentric cable is homogeneous, the voltage gradient at any diameter x is given by

$$\frac{d\,v}{d\,x} = \frac{0.868\ V}{x \log_{10} \dfrac{D}{d}} = S \tag{1}$$

where S is the dielectric stress or potential gradient, V the voltage between conductor and sheath, D the diameter of the dielectric, and d the conductor diameter.

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[1] W. I. Middleton and Chester L. Dawes "Voltage Testing of Cables," TRANS. A. I. E. E., Vol. XXXIII (1914), page 1185.

Presented at the Annual Convention of the A. I. E. E., Niagara Falls, Ont., June 26-30, 1922.

If x is expressed in mils, S is given in volts per mil. The stress is obviously a maximum at the surface of the conductor, where $x = d$. If the conductor diameter d, is small as compared with D, the stress S at the surface of the conductor will be large, even with a thick wall of insulation, owing to the concentration of the dielectric flux at the conductor surface. As the diameter of the conductor d increases, D and V remaining fixed, S at first decreases, because of the less concentration of dielectric flux with increasing conductor diameter. When $d = D/2.72$, where 2.72 is the Napierian logarithmic base, S becomes a minimum. The gradient then increases with further increase in d, owing to the lesser thickness of the wall of the dielectric. The relation of the gradient S at the surface of the conductor and the ratio of the conductor to the dielectric diameter for fixed values of V and D is shown in Fig. 1. The minimum gradient occurs when $d/D = 0.368 = 1/2.72$. The curve, however, is quite flat near the point of minimum gradient. Obviously, S is infinite when $d = O$, and when $d = D$.

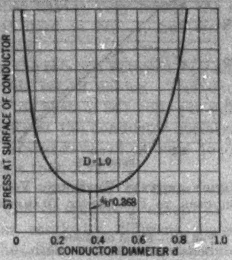

FIG. 1—RELATION BETWEEN STRESS AT SURFACE OF CONDUCTOR AND CONDUCTOR DIAMETER

Impressed voltage and insulation diameter fixed.

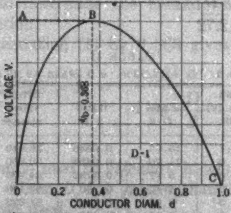

FIG. 2—RELATION BETWEEN ALLOWABLE VOLTAGE AND CONDUCTOR DIAMETER

Maximum stress and insulation diameter fixed.

If the allowable gradient S at the surface of the conductor and the diameter of the dielectric D, be maintained constant, the voltage which may be impressed on the cable

$$V = \frac{S}{0.868} d \log_{10} \frac{D}{d} = 1.15\ S\ d \log_{10} \frac{D}{d} \qquad (2)$$

Fig. 2 shows the relation between V and d, with S and D ($= 1.0$) fixed. The maximum voltage which may be impressed under these conditions, and yet not overstress the dielectric at any point, occurs when $D/d = 2.72$ or when $d/D = 0.368$. The voltage V is obviously zero when $d = O$ and when $d = D$.

When D/d is equal to or less than 2.72, equations (1) and (2) are generally accepted for determining the voltage, the stress, etc. Our experience has always been that these equations give very consistent results. When D/d exceeds 2.72, however, the layers of insulation adjacent to the conductor can be subjected to gradients far in excess of those which the insulation can normally withstand and yet complete rupture does not occur because the gradient in the remaining layers is not sufficient to cause them to rupture.

We have subjected rubber to dielectric stresses three and four times the value at which it normally ruptures by applying voltage to cables having a very small conductor diameter.

The applied voltage was sufficiently high to produce high stresses in the rubber adjacent to the conductor, and yet not rupture the cable. Examination under a high-powered microscope of the rubber after being subjected to these stresses for considerable time, failed to reveal any change in the physical structure of the dielectric.

CABLES HAVING CONSTANT OUTSIDE DIAMETERS BUT VARYING CONDUCTOR DIAMETERS

In order to investigate the effect of large ratios of dielectric to conductor diameters on dielectric stresses we had several special cables made up. It was necessary to make these of rubber as it is difficult to use wrapped insulations, such as paper and cambric, with the small conductor diameters which we used. Moreover, rubber is a more homogeneous dielectric than either of the other two.

The first two sets of cables were made with the object of determining the effect upon breakdown voltage of having a constant outside diameter and variable conductor diameter. The outside diameters were 12/32 in. or 375 mils (9.49 mm.).

With a gaseous dielectric and concentric cylinders having diameter ratios exceeding 2.72, the dielectric at the surface of the inner conductor becomes ionized when the voltage gradient at its surface becomes sufficiently high. This produces corona at the surface of the inner conductor, and its effective diameter is increased by corona formation, as is well-known. Theoretically, this can occur until the corona diameter equals $D/2.72$, when complete rupture occurs without further increase of voltage. These effects will be modified somewhat by the ionization of the air outside the corona diameter.

So far as we know, this effect can only occur in solid dielectrics when there are pockets of occluded gases, and even then the effect cannot be large. In well-made cables we feel that the effect of corona formation on stress distribution is negligible.

Assume that the values of V given by curve $O\,B\,C$, Fig. 2, produce a gradient at the surface of the conductor equal to the disruptive strength of the dielectric. When the impressed voltage exceeds the values given by the portion $O\,B$ of the curve, the dielectric near the conductor is obviously stressed beyond its disruptive strength. So far as the writers know, corona cannot form in such a manner as to increase the effective diameter of the conductor. Many theories as to the effects which this condition of overstress produces in the dielectric have been advanced, such as the carbonizing of the dielectric, etc.

In the cables constructed for investigating this effect, conductors ranging from No. 24 A. W. G. giving a value of $D/d = 18.65$ to No. 3 Stranded (A. W. G.) giving a value of $D/d = 1.44$ were used. Breakdown tests were made on short lengths, the results of which are tabulated in Table I.

TABLE I.

Set No. 1. $D = 12/32$ in. $= 0.375$ in. (9.49 mm.)

Size cond. A. W. G.	Cond. diam. (d) mils	Ratio D/d	Ratio d/D	Break-down voltage	Gradient at cond. surface volts per mil
24 solid	20.1	18.65	0.0536	27,680	942
20	32.0	11.70	0.0853	29,480	748
14	65.0	5.77	0.173	33,940	592
..	90.0	4.17	0.240	35,280	549
8	128.0	2.93	0.342	39,140	568
6	162.0	2.31	0.432	33,490	493
5	186.0	2.02	0.496	31,760	487
2	258.0	1.45	0.688	23,830	494
3 strd.	260.0	1.44	0.694	27,950	587

The insulation showed a dielectric strength of approximately 500 volts per mil when D/d was less than 2.72.

The values of breakdown voltage given in Table I are plotted as kilovolts in Fig. 3, with the ratio d/D as abscissas. With two exceptions, the points lie on a smooth curve. The dotted curve shows the voltage which will give a constant gradient of 500 volts per mil at the surface of the conductor, as the conductor diameter varies. It will be noticed that the two curves coincide, over the range of experiment, for values of d/D greater than 0.368 or 1/2.72. When the value of d/D is less than 0.368 the breakdown curve departs from the constant gradient curve, lying well above it. If the insulation loses its dielectric strength as soon as it becomes overstressed, the breakdown voltage should follow the curve $A\,B\,C$, Fig. 2, as was pointed out by the authors in their 1915 paper[2].

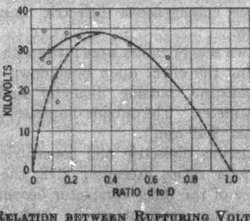

FIG. 3—RELATION BETWEEN RUPTURING VOLTAGE AND THE RATIO OF CONDUCTOR TO INSULATION DIAMETERS FOR DATA IN TABLE I.

Full line—actual breakdown
Dotted line—calculated breakdown
Maximum stress—500 V/mil

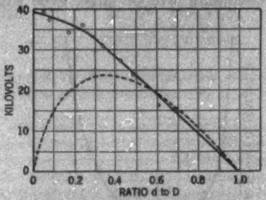

FIG. 4—RELATION BETWEEN RUPTURING VOLTAGE AND THE RATIO OF CONDUCTOR TO INSULATION DIAMETERS FOR DATA IN TABLE II

Full line—actual breakdown
Dotted line—calculated breakdown
Maximum stress—347 V/mil

Our experience that the breakdown voltage usually followed the straight line $A\,B$ more closely than the the curve $O\,B$, Fig. 2, led us to adopt the following formula for cables having conductor diameters less than $D/2.72$

$$S = \frac{0.868\,V}{d_e \log_{10} \dfrac{D}{d_e}} = \frac{5.44\,V}{D} \qquad (3)$$

where $d_e = \dfrac{D}{2.72}$

TABLE II.

Set No. 2. $D = 12/32$ in. $= 0.375$ in. (9.49 mm.)

Size cond. A. W. G.	Cond. diam. (d) mils	Ratio D/d	Ratio d/D	Break-down voltage	Gradient at cond. surface volts per mil
24 solid	20.1	18.65	0.0536	39,940	1355
20	32.0	11.70	0.0853	38,250	971
14	65.0	5.77	0.1732	34,900	612
..	90.0	4.17	0.240	36,760	571
8	128.0	2.93	0.342	31,630	460
6	162.0	2.31	0.432	26,870	395
5	186.0	2.02	0.496	23,980	368
3	229.0	1.637	0.610	16,750	297
2	258.0	1.453	0.688	15,720	326

The cables whose breakdown characteristics are given in Table I and Fig. 3 follow this law very closely. The breakdown voltage actually becomes less when the conductor diameter becomes less than $D/2.72$, showing that the insulation between the conductor and the diameter $D/2.72$ adds nothing to the dielectric strength of these particular cables, but rather causes it to be less.

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[2] loc. cit.

Table II gives data on another set of cables (No.2), similar to that shown in Table I. These cables were made of rubber having very nearly the same composition as that used in No. 1, but were cured by a different method.

Fig. 4 gives the relation between d/D and breakdown voltage for this set of cables. The dotted curve is calculated on the basis of 347 volts per mil, the average of the gradients at the conductor surfaces for the last four cables, whose ratio of outside to conductor diameter was less then 2.72.

Although the dielectric of these cables is nearly the same as that of set No. 2, except for cure, this set of cables has markedly different dielectric characteristics. The dielectric stress calculated for large values of d/D is only about 0.7 that for the first set of cables and yet with small values of d/D it has much greater dielectric strength. That is equation (3) is not applicable to these cables. A comparison of the results obtained with these two cables demonstrates the difficulty of obtaining consistent results under all conditions.

CABLES HAVING CONSTANT CONDUCTOR DIAMETERS BUT VARYING OUTSIDE DIAMETERS

In order to determine the effect on the dielectric strength of cables of increasing the wall of insulation with a fixed conductor diameter, another set of cables was made up. In this set a No. 24 A. W. G. conductor having a diameter of 20.1 mils (0.51 mm.) was used. The diameters of the insulation varied from 3/32 in. (2.38 mm.) to 10/32 in. (7.94 mm.) giving values of D/d ranging from 4.69 to 15.55.

The results obtained with these two sets of cables were used to determine the breakdown constant K of the insulation.

Dividing equation (1) by 0.868 gives

$$1.15\,S = K = \frac{V}{d \log \dfrac{D}{d}} \tag{4}$$

This equation is used to calculate K when D/d is less than 2.72. When D/d is greater than 2.72 equation (3) is likewise used.

$$K = \frac{V}{d_e \log \dfrac{D}{d_e}} = \frac{6.27V}{D} \tag{5}$$

The constant K is the dielectric strength of the insulation multiplied by the constant 1.15. If the breakdown voltage follows these laws the values of K obtained by using equations (4) and (5) should be practically constant. As the values of D/d for all the cables in Table III were greater than 2.72, only equation (5) was used in the computation of K, for these particular cables.

TABLE III.

Set No. 3—No. 24 A. W. G. Cond. Diam. (d) = 20.1 mils (0.510 mm.)

Outside diam.	Ratio D/d	Breakdown voltage	k
3/32 in.	4.69	9,930	663
4/32	6.22	13,600	681
5/32	7.77	17,800	715
6/32	9.33	23,000	769
8/32	12.45	27,300	685
10/32	15.55	34,200	685

The values of K calculated, using equation (5) and given in Table III, are plotted in Fig. 5.

With small values of D/d, K increases slightly. For large values of D/d, K is practically constant. The breakdown voltage of this set of cables followed the law given by equations (4) and (5) very closely.

EFFECT OF STRESS ON PERMITTIVITY

It is well-known that the dielectric constant or permittivity of a dielectric increases under dielectric stress. We felt that this fact might offer a partial explanation, at least, of the ability of the inner layers of cables to withstand voltage gradients far in excess of the normal rupturing gradients of the dielectric, and yet apparently show no signs of rupture.

If the capacitance of that part of the cable nearer the conductor increased a sufficient amount, there would obviously be a less percentage of the total voltage across these layers under high stress, hence the cable would automatically grade itself.

To determine whether or not there was any considerable change of capacitance under these conditions, a special cable was made up. The dimensions and cross-section of this cable are shown in Fig. 6. Our idea was to make a cable having a very heavy wall of insulation and also an extremely high value of D/d. Between the conductor and outside, a concentric conducting cylinder was made into the cable as a means of determining the potential at some intermediate distance between the conductor and the outer surface of the insulation. Because of greater ease of manufacture, a 0.038-in. (0.97 mm.) lead sheath was used for this intermediate conducting cylinder. The copper was No. 12 A. W. G. having a diameter of 0.081-in. (2.06

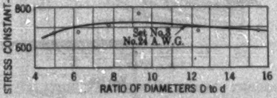

FIG. 5—RELATION BETWEEN STRESS CONSTANT K AND THE RATIO OF INSULATION AND CONDUCTOR DIAMETERS FOR CABLES IN TABLE III

mm.). The inside diameter of the lead was 0.328 in. (8.34 mm.) giving 4.05 as the value of D/d for this inside portion of the cable. This value of D/d is well above the critical value of 2.72 and any phenomena developing under these conditions should be apparent in this cable. The outer diameter of the lead was 0.404 in. (10.3 mm.) and the cable diameter was 1.0 in. (25.4 mm.) giving 2.48 as the value of D/d for this outer portion of the cable. The ratio of outside to conductor diameter is only slightly less than the critical value of 2.72.

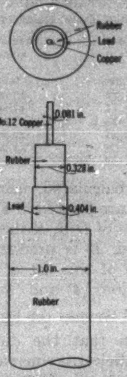

Fig. 6—Cable with Intermediate Sheath

Approximately 100-ft. lengths of this cable were immersed in water. The electrostatic capacitance was then measured with low-voltage, 25-cycle, alternating current by means of a deflecting dynamometer, the cable capacitance being obtained by direct comparison with a standard condenser.

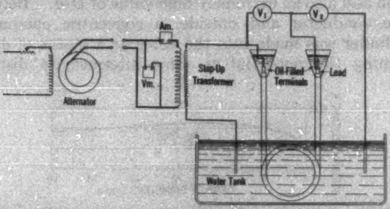

Fig. 7—Diagram of Connections for Stress Tests on Cable with Intermediate sheath

The cable was then connected to the secondary of a step-up transformer, the connections being shown in Fig. 7. The potential difference between the copper and lead and that between lead and ground was measured by means of two vibrating electrostatic voltmeters V_1 and V_2, a description of which has already been published by one of the authors.[3] The capacitance of these instruments is practically nil as compared with the capacitances across which they were connected, hence they did not disturb the potential relations within the cable.

Fig. 8 gives the results obtained from a typical test. The voltage, copper to lead and lead to ground, are plotted as ordinates with the total voltage from copper to ground as abscissas. The ratios between these two voltages remained practically constant until the voltage from copper to lead reached 22 kv. when there was a noticeable unsteadiness in the vibrations of both electrostatic instruments. As the applied voltage was being increased, the unsteadiness of V_1 became pronounced and at 22.8 kv. its reading dropped to zero, showing that the insulation between copper and lead had ruptured. Simultaneously, the reading of V_2 jumped to that corresponding to line voltage. The voltage was then raised slowly until at 56.5 kv. the cable punctured from lead to ground. At the instant of breakdown between copper and lead the stress at the surface of the conductor was 600 volts per mil. Using equation (3), the stress at the diameter $D/2.72$ was 377 volts per mil. The stress at the surface of the lead when the entire cable broke down at 56.5 kv. was 308 volts per mil. Three tests similar to the above were made, and the cable broke down copper to lead at practically this same voltage, the voltages being 23.8 kv. and 26.0 kv. In the subsequent tests the breakdown voltages from lead to ground were much higher than 56.5 kv., the average being approximately 70 kv.

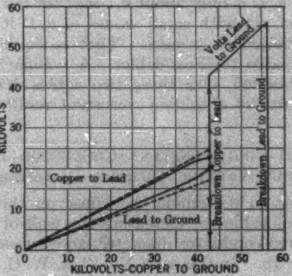

Fig. 8—Relation between Potentials—Copper to Intermediate Sheath, Intermediate Sheath to Ground, and Copper to Ground

Full lines—experimental values
Dotted lines—calculated values

The voltage between copper and lead and that from lead to ground were then calculated, using the measured values of alternating-current capacitance. The calculated voltages are shown by the dotted lines, Fig. 8. It will be noted that the increase of capacitance of the inner portion of the cable, which was under high stress, over that of the outer portion of the cable, which was under only moderate stress, is only of the order of 5 per cent except at the instant of breakdown, when it is slightly greater than this. This 5 per cent change in capacitance agrees very closely with other measurements which we have made to determine the change of capacitance caused by electrostatic stress. We feel that these tests demonstrate that the stress across the inner layers of a cable having a large ratio D/d is not relieved to any considerable extent by a change of capacitance produced by the stress. It also demonstrates that for this particular cable, the wall of insulation within a diameter of $D/2.72$ adds nothing to the dielectric strength of the cable.

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[3] Trans. A. I. E. E., Vol. XXXV (1916), page 133.

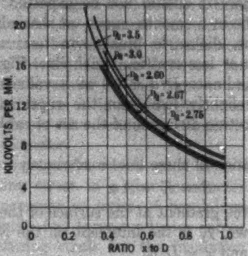

FIG. 9—RELATION BETWEEN GRADIENTS THROUGHOUT THE WALLS OF INSULATION AND THE RATIO x/D

Breakdown tests of F. Fernie.

LAW OF BREAKDOWN FOR VALUES OF D/d GREATER THAN 2.72

As was stated earlier in the paper, our object in making these numerous tests was, if possible, to determine some relation between the breakdown voltage and the stresses within the insulation for large values of D/d.

In an article appearing recently in *Beama*,[4] F. Fernie submits test data showing that several different cables, tested by him, all rupture with practically equal potential gradients at the outer surface of the insulation. The results are tabulated in Table III of his paper. The authors have examined this paper very carefully. In checking his values of gradient given in the last column of Table III, we find several values in error. The values of stress calculated by us, using his data, are not so nearly equal as his figures indicate. However, even then the difference can be readily accounted for by the erratic nature of breakdown tests already discussed. Even if these cables did break down at values of gradient at the outer surface of the insulation which were practically equal, we do not feel that it is at all rational to consider the breakdown voltage a function of dielectric strength of the outer layers where the gradient is a minimum.

Fig. 9 shows the calculated gradient throughout the insulation of each cable at the instant of breakdown. The gradient is plotted with kv. per mm. as ordinates and values of x/D as abscissas for each cable, where x is any diameter within the insulation. With fixed values of d and D and homogeneous insulation, the stress at each diameter x is inversely proportional to x (Eq. (1)). Therefore, each of these curves is a rectangular hyperbola. That is, the gradient at each point of Curve 1, Fig. 9,

$$S_1 = \frac{K_1}{(x/D)} \qquad (6)$$

and the stress at each point on curve 2

$$S_2 = \frac{K_2}{(x/D)} \qquad (7)$$

where K_1 and K_2 are constants.

For any given value of x/D

$$S_1/S_2 = K_1/K_2 \qquad (8)$$

That is, the ratio of ordinates of any two curves for each value of x/D is constant for all values of x/D. If the gradients at the outer surfaces of the insulation of two cables are equal, they will be equal at all values of x/D for the two cables. If cables break down for equal values of gradient in the outer layers, the gradients in the inner layers for each value of x/D, as far as a given curve extends, must be equal.

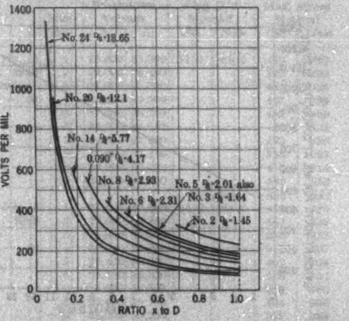

FIG. 10—RELATION BETWEEN GRADIENTS THROUGHOUT THE WALLS OF INSULATION AND THE RATIO x/D FOR CABLES IN TABLE II

An examination of Fig. 9 shows that the cables broke down for nearly equal values of gradient at the ratios of x to D between 0.33 and 0.39 which correspond practically to the critical ratio of D to d of 2.72.

We find that if the values of gradient at the outer surfaces of our cables No. 1 and No. 2 be plotted as ordinates and d/D as abscissas, in one case a perfectly straight line results, and in another the plot is slightly curved. We do not feel that this is important, however, as it is merely the result of higher gradients existing within the inner layers of the cable.

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[4] F. Fernie, "Insulation Experiments," *Beama* Sept. 1921 page 244.

On analyzing the tests made on the sets of cables No. 1 to No. 3 inclusive, the gradients throughout the insulation as ordinates and values of x/D as abscissas for each cable were plotted. A typical example for set No. 2 is shown in Fig. 10. The insulation is assumed homogeneous in every case.

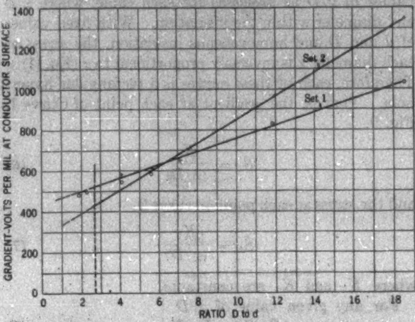

Fig. 11—Relation between Conductor Stress and Ratio of Insulation to Conductor Diameters for Cables in Tables I and II

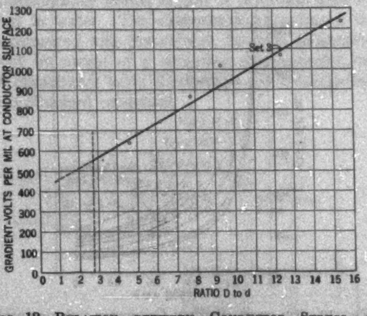

Fig. 12—Relation between Conductor Stress and Ratio of Insulation to Conductor Diameters for Cables in Table III

The upper extremity of each curve is the gradient at the conductor surface at the instant of breakdown. It will be noted that if a curve be drawn through these upper extremities, a curve resembling a rectangular hyperbola results. Therefore, if these gradients at the conductor surface be plotted with the reciprocal of d/D or D/d as ordinates, the plot should be nearly a straight line.

Fig. 11 shows these plots for the cables in sets No. 1 and No. 2. It will be noted that the points, particularly at the larger values of D/d, lie on practically a straight line. It should not be expected that every point will lie in a smooth curve, as, has already been pointed out, dielectric breakdown tests are certain to be more or less erratic. Each line, Fig. 11, intercepts the ordinate $D/d = 1.0$ at a value of gradient only very slightly less than the rupturing gradient of the respective dielectric of the set of cables which it represents.

The equation of these lines is obviously

$$S = K + A\,x \qquad (9)$$

where S is the gradient at the surface of the conductor at breakdown, K is the intercept on the S-axis, A is a constant and $x = D/d$.

Fig. 12 gives similar plots for the cables in set No. 3 having conductors of No. 24 A. W. G. and varying walls of insulation.

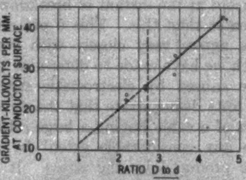

Fig. 13—Relation between Conductor Stress and Ratio of Insulation and Conductor Diameters for Cables in F. Fernie's Paper

Fig. 13 gives similar curves using values obtained from F. Fernies' paper.[5] The plot given by these points is a straight line within the precision of results obtained from any set of breakdown tests. The intercept on the ordinate $D/d = 1.0$ gives a value of gradient about 0.7 the rupturing gradient of the insulation.

All the test data which we have available seem to indicate that for any given dielectric a straight-line law exists between the gradient at the conductor surface at breakdown and the ratio of outside to conductor diameters (D/d) for values of D/d greater than 2.72. However, we feel that further investigation is needed along this line, before this relation be accepted as final.

Stresses in Three-Conductor Cables

At the present time, there are two common methods of calculating the maximum stress in a three-conductor cable.

In the first method, which is the one used by most engineers until recently, the maximum stress for a three-conductor cable was calculated by the same formula as that used for a single-conductor cable of the same size of conductor and having a wall of insulation equal to the total wall between the conductors of the three-conductor cable.

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[5] loc. cit.

The second method is by means of a formula recently published in the JOURNAL and PROCEEDINGS of the A. I. E. E.[6] Here again the stress in a three-conductor cable is calculated by the same formula as for a single-conductor cable, but the wall of insulation is assumed to be equal to the distance between the conductor surface and the center of the three-conductor cable. A correction factor is involved, dependent upon the relation between the conductor insulation and the conductor diameter.

In order to determine which one of these two methods of calculating stress in a three-conductor cable was the more accurate, a series of breakdown tests was made on single- and three-conductor cables.

The rupturing stress for the insulation should be approximately the same with both the single and three-conductor cables.

Of the two foregoing methods, the one which should be accepted as standard is the one which gives the rupturing stress of the insulation of a three-conductor cable more nearly equal to that of a single-conductor cable, having the same kind of insulation.

Tables IV and V give the results of breakdown and calculated stresses for single and three-conductor paper cables.

TABLE IV.

Breakdown Tests—6-ft. Samples—No. 6 A. W. G.
PAPER

Cable	Sample	Breakdown Voltage		*d* log *D*/*d* Method		Max. stress Method	
		Y	Δ	Old	New	Old	New
Three-Cond., No. 6	1	15,000	25,900	85.6	65.2	263	200
St.—5/64-in. Wall	2	17,600	30,400			308	235
—5/64-in. Jacket	3	20,400	35,300			358	272
Three - Phase — 60	4	15,600	27,000			274	208
cycles	5	16,800	29,100			295	224
	6	17,200	29,800			302	229
	7	17,600	30,500			309	235
	8	23,000	39,800			403	307
	9	18,000	31,200			316	240
	10	18,800	32,500			329	251
				Average		316	240
Three-Cond., No. 6	1	21,400	37,000	85.6	65.2	375	285
St.—5/64-in. Wall	2	19,600	33,900			343	261
—No Jacket	3	17,600	30,500			309	235
Three - Phase — 60	4	20,000	34,600			351	266
cycles	5	15,800	27,300			277	211
	6	19,600	33,900			343	261
	7	18,200	31,500			319	243
				Average		331	252
Single-Cond., No. 6	1	49,600		80.6		534	
St.—5/32-in. Wall	2	37,200				402	
Single - Phase — 60	3	36,800				396	
cycles	4	24,800				267	
	5	31,200				336	
	6	33,200				357	
	7	30,000				323	
	8	37,200				402	
	9	36,000				388	
	10	28,000				301	
				Average		371	

Table VI gives the results of breakdown and calculated stress for single-conductor and three-conductor varnished cambric cables.

TABLE V.

Breakdown Test 6 ft. Samples—No. 2 A. W. G. Paper.

Cable	Sample	Breakdown Voltage		*d* log *D*/*d* Method		Max. stress Method	
		Y	Δ	Old	New	Old	New
Three-Cond., No. 2	1	22,800	38,600	99.4	77.7	338	255
St.—5/64-in. Wall	2	21,600	37,300			326	241
—5/64-in. Jacket	3	26,800	46,300			405	300
Three - Phase — 60	4	18,800	32,500			284	210
cycles	5	21,800	37,700			330	244
	6	31,000	50,500			432	346
	7	19,200	33,200			291	215
	8	35,000	60,500			529	391
	9	24,600	42,500			372	275
	10	20,600	35,600			311	230
				Average		362	271
Single-Cond., No. 2	1	31,200		87.3		310	
St.—5/32-in. Wall	2	40,800				406	
Single - Phase — 60	3	31,600				314	
cycles	4	30,800				306	
	5	27,600				274	
	6	33,800				336	
	7	42,800				426	
	8	30,400				302	
	9	28,800				286	
	10	36,000				358	
				Average		332	

The breakdowns were all made at 60 cycles and by raising the voltage at the rate of approximately 1000 volts per second. The single-conductor cables were broken down with single-phase voltage between conductor and lead and the three-conductor cables with three-phase voltage between conductors, the lead sheath being grounded and connected to the neutral point of the Y-connected transformers.

TABLE VI.

Breakdown Tests—6-Ft. Samples—No. 6 A. W. G.
CAMBRIC

Cable	Sample	Breakdown Voltage		*d* log *D*/*d* Method		Max. stress Method	
		Y	Δ	Old	New	Old	New
Three-Cond., No. 6	1	25,000	43,300	84.0	64.0	448	339
St.—5/64-in. Wall	2	22,000	38,100			393	298
—5/64-in. Jacket	3	27,000	46,700			482	366
Three - Phase — 60	4	25,000	43,300			447	339
cycles	5	27,000	46,700			482	366
	6	24,000	41,600			430	326
	7	24,000	41,300			430	326
	8	21,600	37,400			386	293
	9	23,200	40,200			415	314
	10	26,000	45,000			465	353
				Average		438	332
Three-Cond., No. 6	1	24,600	42,600	84.0	64.0	440	334
St.—5/64-in. Wall	2	25,000	43,300			447	339
—No Jacket	3	18,800	32,500			336	255
Three - Phase — 60	4	30,000	51,900			537	407
cycles	5	22,400	38,800			402	304
	6	24,600	42,600			440	334
	7	28,000	48,500			502	380
	8	22,600	39,100			404	306
	9	29,000	50,200			517	393
	10	20,800	36,000			372	282
				Average		440	333
Single-Cond., No. 6	1	47,200		79.0		518	
St.—5/32-in. Wall	2	43,600				480	
Single - Phase — 60	3	47,000				516	
cycles	4	48,800				537	
	5	50,000				550	
	6	41,600				457	
				Average		510	

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[6] R. W. Atkinson, "The Dielectric Field in an Electric Power Cable," TRANS. A. I. E. E. Vol. XXXVIII (1919), page 971. Davis & Simons, "Maximum Allowable Working Voltages in Cables," A. I. E. E. JOURNAL, January 1921.

TABLE VII.

1000-Cycle Capacitance Tests—Paper

Copper temp.	68°F = 20°C	105°F = 40.5°C	148°F = 64.5°C	175°F = 79.5°C	200°F = 93.3°C
Lead temp.	68°F = 20°C	78°F = 25.5°C	94°F = 34.5°C	105°F = 40.5°C	113°F = 45.0°C
Copper No. 1 Layer	3720	3940	3965	4020	4140
No. 1 Layer No. 2 Layer	2910	2940	3000	3050	3110
No. 2 " No. 3 "	3770	3875	3840	3870	3900
No. 3 " No. 4 "	5530	5550	5560	5610	5640
No. 4 " Lead	5560	5590	5590	5840	5900

TABLE VIII.

1000-Cycle Capacitance Test—Cambric Sample

Copper temp.	71°F = 21.7°C	99°F = 37.2°C	148°F = 64.5°C	175°F = 79.5°C	200°F = 93.3°C
Lead temp.	71°F = 21.7°C	80°F = 26.7°C	101°F = 38.3°C	115°F = 46.1°C	121°F = 49.4°C
Copper No. 1 Layer	3075	3230	3530	3600	3730
No. 1 Layer No. 2 "	4540	4730	5170	5220	5320
No. 2 " No. 3 "	4650	4780	5030	5050	5080
No. 3 " No. 4 "	6310	6450	6730	6850	6850
No. 4 " Lead	7300	7450	7770	8000	8030

TABLE IX.

Measured Voltages—Grounded Lead Sheath to Layers of Copper Strands

Paper Cable

Copper temp.	68°F = 20°C	105°F = 40.5°C	148°F = 64.5°C	175°F = 79.5°C	200°F = 93.3°C
Lead temp.	68°F = 20°C	78°F = 25.5°C	94°F = 34.5°C	105°F = 40.5°C	113°F = 45.0°C
Lead to Copper	10,000	10,000	10,000	10,000	10,000
" No. 1 Layer	7,000	8,000	8,050	8,110	8,250
" No. 2 "	5,140	5,200	5,250	5,400	5,550
" No. 3 "	2,980	3,000	3,000	3,100	3,250
" No. 4 "	1,480	1,500	1,490	1,500	1,550

TABLE X.

Measured Voltages—Grounded Lead Sheath to Layer of Copper Strands

Cambric Cable

Copper temp.	71°F = 21.7°C	99°F = 37.2°C	148°F = 64.5°C	175°F = 79.5°C	200°F = 93.3°C
Lead temp.	71°F = 21.7°C	80°F = 26.7°C	101°F = 38.3°C	115°F = 46.1°C	121°F = 49.4°C
Lead to Copper	10,000	10,000	10,000	10,000	10,000
" No. 1 Layer	6,950	7,000	7,100	7,200	7,350
" No. 2 "	4,900	5,000	5,200	5,400	5,650
" No. 3 "	2,950	3,000	3,100	3,350	3,500
" No. 4 "	1,400	1,400	1,450	1,600	1,650

TABLE XI.

Voltage Between Successive Layers—Paper Sample

Copper temp.	68°F = 20.0°C	105°F = 40.5°C	148°F = 64.5°C	175°F = 79.5°C	200°F = 93.3°C
Lead temp.	68°F = 20.0°C	78°F = 25.5°C	94°F = 34.5°C	105°F = 40.5°C	113°F = 45°C
Copper No. 1	2100	2000	1950	1900	1750
No. 1 Layer No. 2 Layer	2760	2800	2800	2700	2700
No. 2 " No. 3 "	2160	2200	2250	2300	2300
No. 3 " No. 4 "	1500	1500	1510	1600	1700
No. 4 " Lead	1480	1500	1490	1500	1550

TABLE XII.

Voltages Between Successive Layers—Cambric Sample

Copper temp.	71°F = 21.7°C	99°F = 37.2°C	148°F = 64.5°C	175°F = 79.5°C	200°F = 93.3°C
Lead temp.	71°F = 21.7°C	80°F = 26.7°C	101°F = 38.3°C	115°F = 46.1°C	121°F = 49.4°C
Copper No. 1	3050	3000	2900	2800	2650
No. 1 Layer No. 2 Layer	2050	2000	1900	1800	1700
No. 2 " No. 3 "	1950	2000	2100	2050	2150
No. 3 " No. 4 "	1550	1600	1650	1750	1850
No. 4 " Lead	1400	1400	1450	1600	1650

It should be noted that the rupturing stresses of the three-conductor cables when calculated by the old method are nearly the same as for the single-conductor cables, while the stresses calculated by the new method are considerably lower.

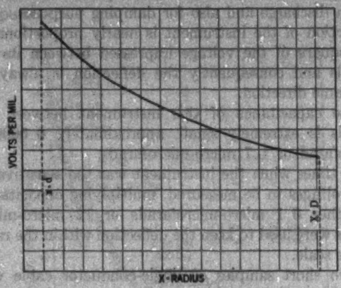

FIG. 14—TYPICAL POTENTIAL-GRADIENT CURVE

EFFECT OF INTERNAL HEATING ON VOLTAGE GRADIENT WITHIN CONCENTRIC INSULATION

The general shape of the potential gradient or stress curve for a homogeneous wall of concentric insulation calculated by the logarithmic formula, equation (1), is shown in Fig. 14.

If the wall of insulation is not homogeneous, but made up of multiple layers of insulating materials having different dielectric constants, the voltage distribution throughout the wall may be calculated by the formula

$$V_0 = V_1 + V_2 + V_3 + \ldots\ldots V_n$$

$$= \frac{2Q}{K_1}\log_e r_1/r + \frac{2Q}{K_2}\log_e r_2/r_1 + \frac{2Q}{K_3}\log_e r_3/r_2 + \ldots\ldots \qquad (10)$$

$$\frac{2Q}{K_n}\log_e r_n/r_{n-1}$$

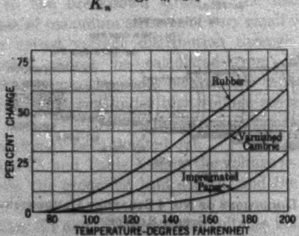

FIG. 15—PER CENT CHANGE OF DIELECTRIC CONSTANT WITH CHANGE OF TEMPERATURE FOR INSULATING MATERIALS

where V_0 is the total voltage across the wall of insulation

V_1, V_2, V_3 are the respective voltages across the first, second, third layers of insulating material

Q is the electrostatic charge on the surface of each layer of insulating material

K_1, K_2, K_3 are the respective dielectric constants of the layers of insulating material

r is the radius of the conductor

$r_1, r_2, r_3, \ldots r_n$ are the radii of the layers of insulating material.

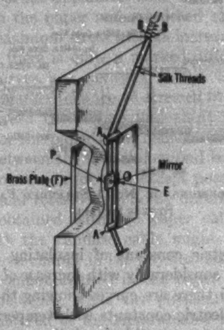

FIG. 16—LOW-CAPACITANCE ELECTROSTATIC VOLTMETER

By employing multiple layers of insulating materials with the proper relative values of dielectric constants, it is possible to reduce considerably the maximum voltage stress at the surface of the conductor and increase the stresses in the outer layers of the insulation.

This method of insulating cables is commonly referred to as "grading" and theoretically results in a cable that will withstand a higher impressed voltage than a non-graded cable, other factors being equal.

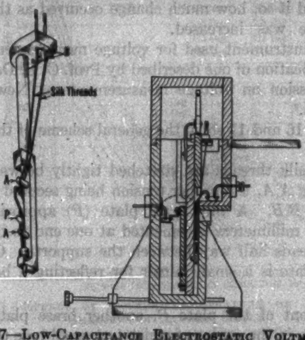

FIG. 17—LOW-CAPACITANCE ELECTROSTATIC VOLTMETER

Several excellent papers[7] have been published on the subject of "grading of cables."

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[7] E. Jona, *Trans. of International Elec. Congress*, St. Louis, 1904, page 550.
A. Russel, *London Electrician*, Vol. 60, 1907, page 160.
H. S. Osborne, TRANS. A. I. E. E., Vol. 29, 1910, page 1553.

An insulated cable carrying current must dissipate energy in the form of heat, and the source of this energy is the $I^2 R$ loss in the conductor. The heat flows from the conductor to the surrounding medium with the result that the conductor is at a much higher temperature than the outside of the insulation.

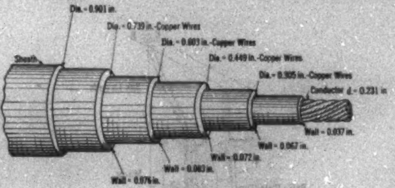

Fig. 18—Dimensions of No. 4 Stranded Paper-insulated Stress Sample

The dielectric constant of insulating materials increases very considerably with increase of temperature. In Fig. 15 there are curves showing the average increase of dielectric constants with temperature for the three most common cable insulating materials.

Therefore, theoretically, the insulation nearest the conductor of a cable carrying current should have a higher dielectric constant than the insulation farther from the center with the result that the voltage distribution throughout the wall of insulation should change as the temperature increases.

The following tests were made to determine whether or not the voltage distribution followed the theoretical law, and if so, how much change occurred as the temperature was increased.

The instrument used for voltage measurements was a modification of one described by Prof. C. L. Dawes in a discussion on voltage measurements at New York in 1916.[8]

Figs. 16 and 17 show the general scheme of the voltmeter.

Two silk threads are stretched tightly between two supports *A A*, the proper tension being secured by the springs *B B*. A thin brass plate (*P*) approximately 6 by 11 millimeters is cemented at one end to the two silk threads half way between the supports. On this brass plate is a small mirror for reflecting a beam of light.

In front of the plate *P*, another brass plate *E* is fastened, in the center of which is a small hole through which a beam of light enters to and leaves from the mirror. These two brass plates are connected together electrically by a flexible metal filament for one terminal of the instrument. The other terminal of the instrument is a small plate *F*, secured to the other side of the hard-rubber barrier. This barrier acts as a dielectric to prevent breakdown between the terminals.

Because of the inertia and high damping of the moving plate, it does not vibrate, as in the original instrument, but gives a steady deflection with constant voltage. It is immersed in oil to prevent corona and brush discharge and also for damping purposes. The deflection of the instrument is nearly proportional to the square of the voltage impressed between its terminals and consequently the deflection is always in the same direction.

The capacitance of this instrument between terminals is extremely small, approximately 0.0000017 microfarad or 1.7 micro-microfarads.

At times when the instrument was too sensitive for the voltages to be measured, multiplying capacitances of either 3.1 micro-microfarads or 12 micro-microfarads were used to keep the deflection within the range of the scale.

Two short samples of single-conductor cable were manufactured upon which measurements could be made —one sample with paper insulation and one sample with varnished cambric insulation. Each sample consisted of a No. 4 A. W. G. stranded copper conductor with a total wall of insulation of approximately 9/32 in. (7.1 mm.), and a lead sheath. At four different points in the walls of insulation, layers of No. 36 A. W. G. bare copper strands were spiraled the length of the sample between layers of the insulating material. Figs. 18 and 19 show the dimensions and locations of the copper strands.

Thermocouples were placed in the conductors and in the lead sheaths of both samples so that it was possible to know accurately the temperature of each.

Sixty-cycle alternating current was applied to the samples from a current transformer and voltage measurements were made with an impressed voltage between conductor and lead of 10,000 volts.

The minimum capacitance between successive layers of copper strands was 950 micro-microfarads. It is evident that because of its small capacitance the electrostatic voltmeter already described could be used to measure voltages between layers of copper strands without disturbing the voltage distribution through the wall of insulation.

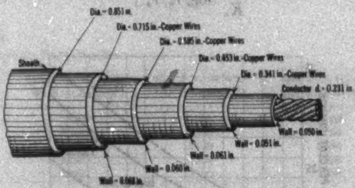

Fig. 19—Dimensions of No. 4 Stranded Cambric-insulated Stress Sample

The voltage measurements were so made that one side of the voltmeter was constantly at ground potential.

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[8] Transactions of A. I. E. E., Vol. XXXV, Part 1, page 133.

Tables VII and VIII show the results of 1000-cycle capacitance tests made on the samples at the various temperatures.

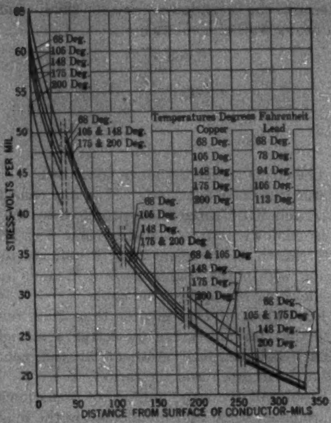

Fig. 20—Effect of Copper Temperature on Potential Gradient of Paper Cable
Four-stranded 0.295-in. wall impregnated paper
Temperature in degrees fahrenheit

The increase of capacitance for the paper cable is small, being only 11.3 per cent for the wall of insulation nearest the conductor and 6.1 per cent for the wall farthest from the conductor. The capacitance measurements indicate that any change in voltage distribution with increase of internal temperature is small, and, except in cases where the insulation is working very close to the breakdown stress of the material, the decrease of maximum stress is of very small value.

The actual voltage distribution through the wall insulation cannot be calculated from low-voltage capacitance measurements because the capacitance of insulating material under high-voltage stress is somewhat higher than when the stress is practically zero as has already been pointed out.

Table IX and Table X show the voltage as measured between the grounded lead sheath, and the layers of copper strands.

Tables XI and XII show the voltages between successive layers of copper strands as calculated from the data in Tables IX and X.

Figs. 20 and 21 show the potential gradient curves plotted from the data in Tables XI and XII. The curve for each copper temperature is indicated and the corresponding lead temperature is shown in the accompanying chart.

The first tests were made after the samples had been kept in the laboratory for several days so that the total wall of insulation was at room temperature. The potential gradient curves for these temperatures are smooth and continuous, the maximum stress on each layer being the same as the minimum stress on the preceding layer. This might be considered a good check on the accuracy of the apparatus used.

While both the paper and varnished cables show a decrease of maximum stress with an increase of internal temperature, there is quite a marked difference in the two sets of curves.

The most marked change of stresses in the cambric cable is between the second and third layers, while the change for the paper cable comes much nearer the conductor, between the first and second layers. There is no apparent reason for this, except possibly a difference in thermal resistivity. Some difference between the results obtained with the paper cable and those obtained with the cambric cable might be expected. This is due to a change in the physical state of the impregnating compound used in the paper cable with a rise of temperature, while the physical state of the insulating material of the cambric cable remains practically constant.

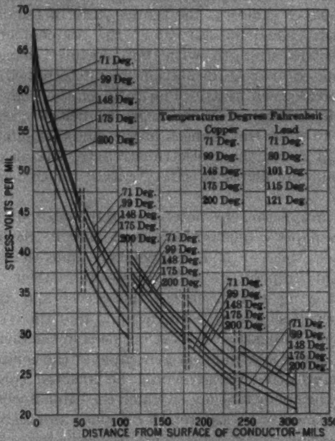

Fig. 21—Effect of Copper Temperature on Potential Gradient of Cambric Cable
Four-stranded 0.270-in. wall varnished cambric
Temperature in degrees fahrenheit

The maximum voltage that can be safely impressed across a wall of insulation depends upon the dielectric strength of the insulating material. The factor of safety for an operating cable is the ratio of the dielectric strength of the insulating material to the maximum stress produced by the working voltage. Either an increase in the dielectric strength or decrease in the maximum stress results in an increase of the factor of safety.

$$\text{Factor of Safety} = \frac{\text{Dielectric Strength}}{\text{Maximum Stress}}$$

If both the dielectric strength and the maximum stress of a cable be changed the effect on the factor of safety would be the ratio of change of dielectric strength to the change of maximum stress.

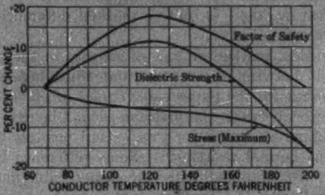

FIG. 22—EFFECT OF DIELECTRIC STRENGTH AND DIELECTRIC STRESS ON THE FACTOR OF SAFETY OF PAPER CABLES
Per cent change in maximum stress vs. conductor temperature
Per cent change in dielectric strength vs. temperature
Per cent change in factor of safety vs. conductor temperature
Paper-insulated cable

Fig. 22 shows the per cent change in maximum stress for the paper cables as the temperature of the cable is increased. There is also shown the per cent changes in dielectric strength with temperature change for impregnated paper insulation as determined from many breakdown tests. The ratio of the changes in dielectric strength to the changes in dielectric stress is plotted to show the changes in the factor of safety.

Fig. 23 shows the dielectric strength, the maximum stress and the factor of safety curves for the cambric cable.

It is interesting to note that the factor of safety for these paper cables is 4 per cent higher at 185 degrees fahrenheit, the A. I. E. E. temperature limit, than it was at normal temperature at 68 degrees fahrenheit.

In studying and discussing the curves and data of this paper, it should be borne in mind that these results are only an indication of what happens in the dielectric because of the internal heat generated at the conductor. The quantitative values would be affected considerably by the conditions under which the cable is working, probably mostly by the relative copper and lead temperatures.

CONCLUSIONS

The experimental evidence given indicates that:

1. For values of D/d equal to or less than 2.72, the potential gradient within a wall of insulation follows the simple logarithmic formula. The maximum stress may be calculated by the formula

$$S = \frac{0.868\,V}{d \log_{10} \dfrac{D}{d}}$$

2. For values of D/d greater than 2.72, the layers of insulation adjacent to the conductor can be subjected to stresses far in excess of those which the insulation can normally withstand and yet complete rupture does not occur.

The following modified formula can be safely used to determine the breakdown stress for small conductors with a heavy wall of insulation

$$S = \frac{0.868\,V}{d_e \log_{10} \dfrac{D}{d_e}}$$

where $d_e = \dfrac{D}{2.72}$

3. The stress across the inner layers of a cable having a large ratio D/d is not relieved to any considerable extent by a change of capacitance produced by the stress.

4. Breakdown tests of a special cable with an intermediate sheath at the point $D/2.72$ indicate that the insulation within the diameter $D/2.72$ adds nothing to the dielectric strength of the cable.

5. For values of D/d greater than 2.72, our data indicate that for any given dielectric, a straight-line law exists between the gradient at the conductor surface at breakdown and the ratio D/d.

6. Results of the large number of breakdown tests which are given show that in calculating the maximum stress in three-conductor cables the wall of insulation should be assumed equal to the total insulation between conductors rather than between conductors and the center of the cable, the delta voltage being used in the computation.

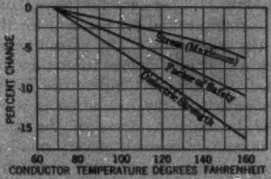

FIG. 23—EFFECT OF DIELECTRIC STRENGTH AND DIELECTRIC STRESS ON THE FACTOR OF SAFETY OF CAMBRIC CABLES
Per cent change in maximum stress vs. conductor temperature
Per cent change in dielectric strength vs. temperature
Per cent change in factor of safety vs. conductor temperature
Varnished cambric-insulated cable

7. Heat generated at the conductor of an insulated cable causes only a small change of capacitance of the insulation nearest the conductor and consequently only a slight "grading" of the cable. No dependence should be put upon the difference of temperature between conductor and outside of the cable to automatically grade the insulation.

Discussion

For discussion of this paper see page 611.

Corona in Air Spaces in a Dielectric

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Review of the Subject.—*The consideration of the extreme care necessary in preparing samples of a dielectric for test for electrical properties led to the investigation of the effect of air spaces, purposely formed of definite thickness and location, upon the power factor. This work in a way is an extension of some work done by Clark and Shanklin and Shanklin and Matson several years ago on air spaces in high voltage cables and wrapped armature coils. In their investigation the effect of assumed air spaces of indefinite thickness, extent, pressure and location was shown by plotting effective resistance from the formula* $R = \frac{E^2}{W}$ *against potential gradient. A characteristic curve was obtained, a sharp inflection point in the curve being interpreted as indicating the starting point of corona.*

In the work by the writer, various materials were investigated both with air spaces excluded as much as possible, and with air spaces of definite thickness, extent, and location at atmospheric pressure. The results were plotted showing variation of power factor with potential gradient. A definite increase in power factor with potential gradient indicated the starting of corona. The thicker air space with a given thickness of dielectric showed the more abrupt change in power factor, and this took place at a lower potential gradient. By plotting power factor against voltage, a maximum was shown indicating that a saturation of ionization was approached which resulted in a decrease in power factor.

By plotting effective resistance assuming the resistance to be in series with the dielectric and to be given by the formula $R = \frac{W}{I^2}$ *a very definite change in R as well as in power factor indicated the beginning of corona. The curve obtained in this way did not possess superior advantages over the plot for power factor for indicating corona and had the disadvantage that the points were somewhat scattered on the upper range of potential gradient.*

The results of the investigation show that:

1. It is extremely difficult to exclude air spaces from a dielectric so that it does not result in corona formation. Corona is shown by a more or less abrupt change in power factor with potential gradient.

2. The abruptness of the change in power factor with potential gradient depends upon the thickness of the air space, the thicker the air space the more abrupt the change.

3. The thicker the air space for any given thickness of dielectric the lower the potential gradient to produce corona.

4. The potential gradient to produce corona not only depends upon the thickness of the air space but also upon the extent of the air space as shown by observations on different areas of air space of the same thickness.

5. A maximum of power factor is reached with potential gradient indicating that saturation of ionization is approached after which the value of power factor decreases with potential gradient.

WHEN measuring dielectric losses and power factor of insulating materials, it is of great importance that air should be excluded from the surfaces of contact with the electrodes and from the interior of the material. At low stresses, the losses and power factor are found to be lower than they should be because of the highly insulating air space. Likewise, the effective area of the material is smaller and consequently the measurements of the electrical properties are incorrect. At higher stresses, the gas spaces become ionized and corona formation results with the attendant increase in losses and power factor.

The phenomenon of corona formation in connection with loss measurements in high voltage cables and armature coils was observed by Clark and Shanklin[1] and was further studied by Shanklin and Matson[2]. In high-voltage cables and armature coils, air spaces no doubt exist which result in corona formation when over-stressed.

In the case of materials built up in the form of cables and coils, it is practically useless to speculate from loss measurements as to the thickness or extent of the air space, its pressure and location. No assumption can safely be made even as to the partial pressures due to entrapped air and the vapors from the materials themselves.

It has been recognized that when an insulating space is filled with a composite dielectric such as a solid material and air having quite different dielectric constants the result is that the dielectric strength of the combination is lower than either one separately. For instance, when air which is a good dielectric and mica which is an excellent dielectric are used in combination, the result is a poorer dielectric than either used separately. This is due to the fact that an increased number of lines of force are concentrated in the air space which has the lower permittivity and this results in breakdown which throws a greatly increased stress upon the mica.

Air in a dielectric in the form of a cable, a wrapped armature coil or test piece with specially applied electrodes, may exist in two ways. Either, it may be in the form of an air film or bubble between layers or between the dielectric and the conductor, or it may be in the form of occluded gases in the interstices of the material. Both no doubt, produce losses at high-voltage stresses, though it is generally believed that air in films or bubbles gives rise to the greater part of the losses. It is impossible to separate the effect of occluded gases since the gases cannot be eliminated except by heat and vacuum, nor can they be excluded except by filling the spaces by some impregnating

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[1] Clark and Shanklin, A. I. E. E. TRANS. Vol. XXXVI, 1917, p. 447.

[2] Clark and Matson, A. I. E. E. TRANS. Vol. XXXVIII, 1919, p. 489.

Presented at the Annual Convention of the A. I. E. E. Niagara Falls, Ont., June 26-30, 1922.

compound. By this process, however, the dielectric properties of the original sample are changed.

Though it is a difficult problem to study the effect of occluded gases on the losses of a dielectric material, the effect of various air spaces, which is by far the greater source of losses, may be studied by actually testing materials in which definite spaces are made and in which their locations are definitely established. It must be understood that the effect of occluded gases is also included in this effect, though in comparison with the former, it may be considered practically negligible.

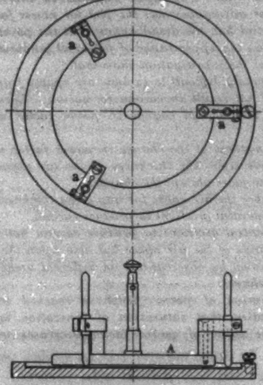

Fig. 1—Testing Electrode

The samples of insulation tested in connection with the effect of air spaces in this investigation, were all in the sheet form. In all cases except for glass, the surface of the material was made plane by fastening to an accurately plane brass disk. In the case of glass, the plane plate was floated upon mercury, the precaution being taken to free as nearly as possible any entrapped air from the under surface. The top electrode applied to the sample was so made that it could be adjusted for any desired air space between it and the specimen. This is shown in Fig. 1. The electrode *A* was a brass disk 7. 5 cm. in diameter with carefully rounded edges and polished surface. This was fitted with three arms *a, a, a,* through the outer ends of which passed three insulating quartz rods which formed a tripod support for the electrode. The quartz rods extended well out from the edge of the disk so that the insulating support was far removed from the electric field, since it is very essential that no dielectric having a different permittivity should be introduced in the air space in an electric field.

The air spaces of uniform thickness were formed between the upper disk and the dielectric by adjusting the quartz rods with spacers. The rods were then clamped in place by tightening the screws in the arms provided for that purpose, as shown in the diagram.

The loss measurements from which the power factor was determined were made with a sensitive electrostatic wattmeter. The current was measured by a sensitive electrometer shunted across a part of the non-inductive resistance of the wattmeter. The testing transformer was of 5 kw. capacity and the voltage was known to have a good sine wave. The voltage was varied by potential taps from the secondary of the transformer except where readings were desired at voltages between these steps. In this case, the voltage from the next step to the transformer, was varied by applying voltages to the primary by a potentiometer arrangement. The current in the potentiometer was quite large so that wave distortion was not introduced. Alternating voltages of 60 cycles were used throughout this investigation.

When materials with air spaces were tested, the potential gradient was increased to a point where there was a quite abrupt change in the losses and the current. The abruptness of this change was dependent upon the thickness and extent of the air space. Graphically the formation of corona is very clearly indicated by plotting power factor which involves both watts loss and current against potential gradient. The potential gradient was taken as volts per centimeter between the plates. For all materials having appreciable air spaces the power factor is low before corona forms, after which it rises rapidly to a maximum and then

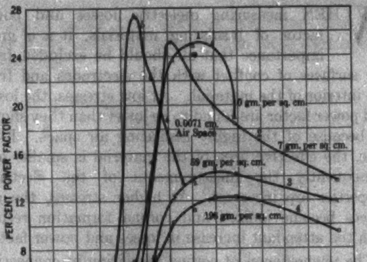

Fig. 2—Corona in Air Spaces

60 Cycles

White India mica, 0.026 cm. thick.

Variation of power factor with pressure on specimen.

again decreases with potential gradient, the sharpness of the fall depending upon the thickness of the air space.

A number of materials were tested with variations of air spaces and the results are shown by the following curves.

A sheet of White India mica about 11 cm. in diameter and 0.023 cm. thick, was selected for test. The specimen was clear and fairly free from air spaces between laminations. It was first tested by placing the mica upon the brass plate and then laying the other electrode on the top surface. The tests were then repeated placing different weights upon the upper electrode. The variation of power factor with potential gradient for various pressures from zero where the weight of the electrode was just supported by the quartz rods to 196 grams per square centimeter are shown in Fig. 1. In these curves, the thickness of the air spaces were not known, though it can be presumed that they decreased with pressure. Curve 5 was obtained by raising the upper electrode a distance of 0.007 cm. above the mica. In each of these cases, there was an air space on each side of the mica presumably of equal thickness except for the last where the greater air space was on the upper side. In general, the power factor at low voltage was always greater for the greater pressure or thinner air space. Likewise, the potential gradient to produce corona was lower for the smaller pressure or thinner air space.

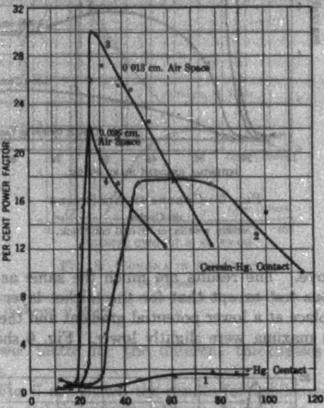

FIG. 3—CORONA IN AIR SPACES
60 Cycles
White India mica, 0.026 cm. thick.

The change in power factor with potential gradient was more gradual the thinner the air space. With a thicker air space, 0.007 cm., the change in power factor was quite abrupt. It is also observed that in all these curves a maximum power factor was reached, after which the power factor decreased in value. In this test, the specimen of mica was not perfectly flat so that the air spaces were not of uniform thickness. A test for power factor was now made with mercury electrodes care being taken to eliminate as far as possible any air films. The result is shown by Curve 1, Fig. 3. It is to be observed that the increase in power factor did not take place until a value of 40 to 45 kilovolts per centimeter was reached. At that point, the increase was not great but the curve clearly gives evidence of an air film either at the surfaces of contact or between laminations. The sample was now fastened to the lower plate by melting a layer of ceresin upon it and pressing the mica upon it by a one half-ton press. Small air spaces were still clearly shown in the surface of contact even though the whole had been heated for some time at about 100 deg. cent. and had been pressed as stated. This fact illustrates how difficult it is to free a test piece from air spaces. The result of the test with mercury contact on the top surface is shown in curve 2. The abrupt change in power factor now occurred at a lower value, about 30 volts per cm. A flat-topped maximum was quickly reached after which the power factor decreased. For an air space of 0.013 cm. the corona started at 22 kv. per cm. and a sharp maximum of 30 per cent power factor was reached at 27 kv. per cm. With a 0.026-cm. air space, corona started at about 19 kv. per cm. and a sharp maximum was reached at 26 kv. per cm. The maximum for this

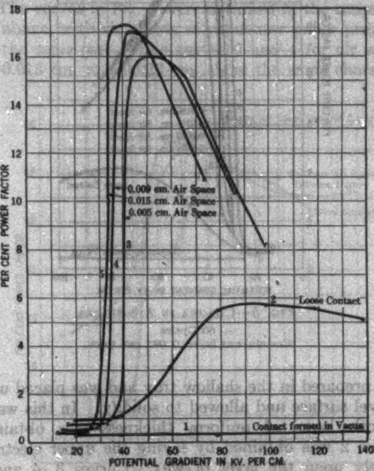

FIG. 4—CORONA IN AIR SPACES
60 Cycles
Ceresin wax layer, 0.025 cm. thick

greater air space was not so great as for the 0.013-cm. air space, which is somewhat contrary to what was generally found. This may have been caused by a change in surface conditions due to the previous application of voltage.

In Fig. 4, are shown the results for a ceresin wax layer 0.025 cm. thick. Curve 1 was obtained by melting the ceresin wax in vacuo in a shallow plane-bottom tray and lowering upon it in vacuo the upper electrode adjusted for the desired thickness. The vacuum was then released and the specimen was allowed to cool. In this way, it was thought that the sample was completely rid of moisture and that air spaces were not included. The results of tests are shown in Curve 1. The curve shows only a very slight uniform rise of power factor up to 140 kv. per cm. Another layer melted in vacuo was prepared in the shallow tray and was placed upon a level surface and allowed to solidify. In this way a smooth layer of uniform thickness was obtained. Curve 2 was obtained by laying the upper electrode loosely upon the layer of wax. Curves 3, 4 and 5 were obtained with air spaces 0.005, 0.009 and 0.015 cm. thick, respectively. As shown by these curves corona formed at lower potential gradients for the thicker air spaces. Likewise, for the thicker air space, the maximum value of power factor was greater, as one would expect if the greater loss took place in the air space.

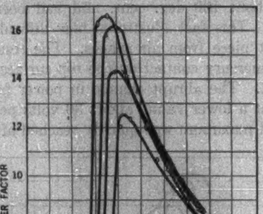

FIG. 5—CORONA IN AIR SPACES
60 Cycles
Ceresin wax layer, 0.041 cm. thick.

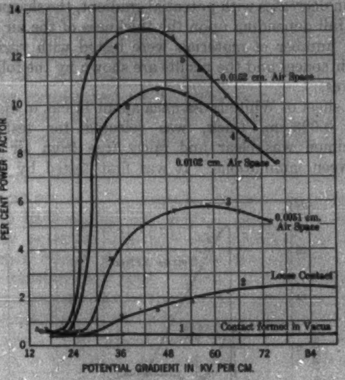

FIG. 6—CORONA IN AIR SPACES
60 Cycles
Ceresin wax layer, 0.056 cm. thick.

In Fig. 5 are shown the results of tests for a thicker layer of wax (0.041 cm.) prepared in the same manner as above. The results are much the same as in the previous test except that for the thicker layer corona took place at a lower potential gradient and the values of the maxima were slightly lower. Fig. 6 shows re-

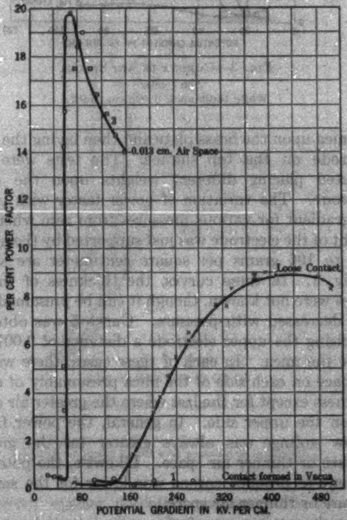

FIG. 7—CORONA IN AIR SPACES
60 Cycles
Three sheets condenser paper impregnated with ceresin in vacuo
Total thickness, 0.006 cm.

sults for a still thicker layer of wax (0.056 cm.). For this thicker layer the potential gradients for corona formation were at still lower values, but the maxima of power factor were lower. Further, with this thicker layer of wax, there is a greater variation in the maxima of power factor for the different thicknesses of air spaces.

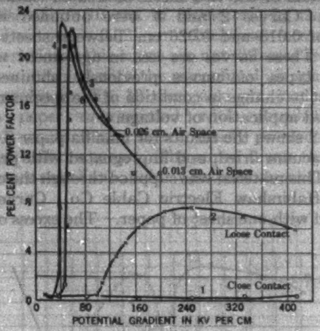

FIG. 8—CORONA IN AIR SPACES
60 Cycles
Six sheets condenser paper impregnated with ceresin in vacuo.
Total thickness, 0.12 cm.

In Fig. 7 are shown the results for condenser paper impregnated in ceresin. Curve 1 was obtained by drying and impregnating and placing the upper electrode on the material in vacuo. In this way all moisture and air should have been completely removed. The curve shows that the power factor is independent of potential gradient. Curve 2 was obtained by placing the upper electrode loosely upon the impregnated condenser paper. Curve 3 was obtained with the same specimen with a 0.013-cm. air space between the impregnated paper and the upper electrode.

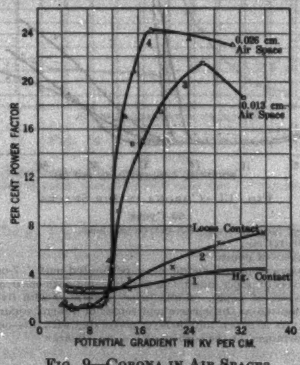

FIG. 9—CORONA IN AIR SPACES
60 Cycles
Glass plate, 0.140 cm. thick.

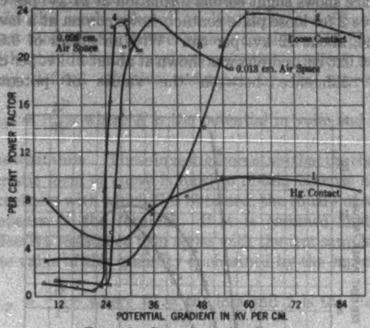

FIG. 10—CORONA IN AIR SPACES
60 Cycles
Treated cloth, 0.023 cm. thick.

The curves in Fig. 8 were obtained in the same way as above, with six sheets of condenser paper prepared in the same way. The curves 3 and 4 for air spaces of 0.013 cm. and 0.026 cm. show the same characteristics, the curve for the thicker air space showing corona at a lower potential gradient but both having about the same maximum value of power factor.

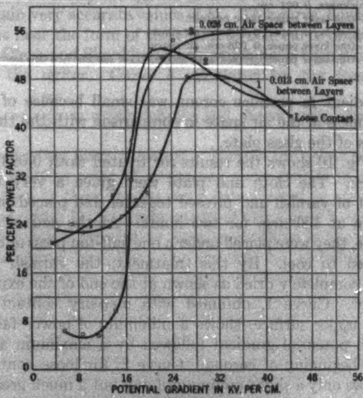

FIG. 11—CORONA IN AIR SPACES
60 Cycles
Treated cloth, 0.023 cm. thick, two layers.
Air spaces between layers.

Fig. 9 shows the curves obtained with a glass plate

0.140 cm. thick. All the curves were obtained with the plate floated upon mercury with especial care taken to exclude as far as possible any air films on the bottom surface. Curve 1 for mercury contact also on the top surface shows slight corona formation at 21 kv. per cm. Curve 2 for loose plate contact shows corona at a lower value, about 12 kv. per cm. With air spaces of 0.013 and 0.026 cm., corona was shown at about 11 kv. per cm. The difference between the values of potential gradient to produce corona was small because of the thinness of the air space in comparison with the thickness of the glass plate.

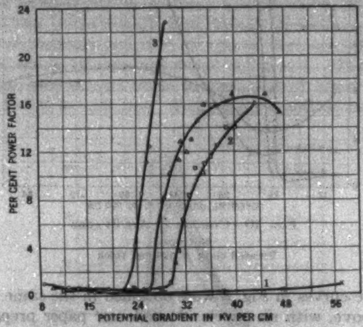

Fig. 12—Corona in Air Spaces

60 Cycles

Manila paper, 15 cm. square, impregnated with petroleum jelly.
Thickness, 0.021 cm.
1—One-layer paper, close contact.
2—One-layer paper, 0.013-cm. air space.
3—One-layer paper, 0.026-cm. air space.
4—One-layer paper covered with second layer having 7.7-cm. hole.

Fig. 10 shows the results for treated cloth 0.023 cm. thick. The cloth and plate were given a very thin coat of varnish and pressed together and placed in an oven at 100 deg. for two hours. At the end of this time, they were placed under a one half-ton press and allowed to cool. By this treatment, the varnish was not completely dried as shown at the end of the experiment. Curve 1, obtained with mercury contact on the upper surface, shows a minimum of power factor with potential gradient followed by a maximum after the beginning of corona. Curve 2, for loose contact, shows only a slight minimum if any but a much greater maximum. Curves 3 and 4 show a very abrupt change in power factor at about 25 and 23 kv. per cm. respectively. With these curves as with others, the falling off of power factor with potential gradient after the maximum was reached was more rapid with the thicker air space. In these curves where the power factor is larger at low voltages, the effect of air spaces in lowering the power factor before corona forms is more clearly shown.

Fig. 11 shows the results for two layers of treated cloth each rubbed with a slight amount of vaseline and each pressed tightly to a surface of each plate. The sample was not heat-treated in any way. Curve 1 was obtained by laying one plate upon the other with the surfaces of the two sheets of treated cloth in loose contact. Curves 2 and 3 were obtained with air spaces of 0.013 and 0.026 cm. between sheets respectively. These curves are less in agreement with the general types of curves previously obtained, due, no doubt to change in condition of the specimen during continued application of voltage.

Fig. 12 shows the results for manilla paper 0.021 cm. thick, vacuum dried, and impregnated with petroleum jelly. This material was supplied through the courtesy of the Habirshaw Electric Cable Co. Curve 1 was obtained with one sheet of paper. The excess of petroleum jelly was removed and air bubbles were excluded and pressure was applied to secure close contact. The curve shows that the power factor was practically independent of voltage. At slightly higher potential gradient, breakdown occurred but there was no noticeable corona formation up to that point. Curves 2 and 3 were obtained with air spaces of 0.013 and 0.026 cm. respectively. The potential gradient was not

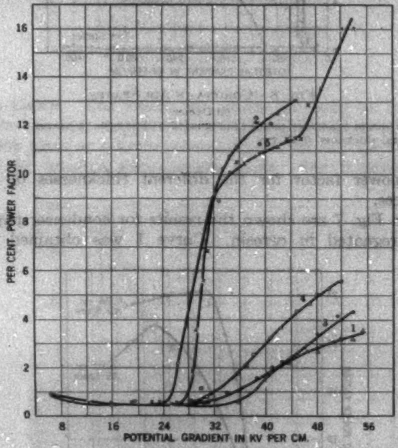

Fig. 13—Corona in Air Spaces

60 Cycles

Manila paper impregnated with petroleum jelly.
Thickness, 0.021 cm.
1—Three layers of paper.
2—Three layers of paper, middle layer perforated with 7.7-cm. hole.
3—Three layers of paper, middle layer perforated with one 0.58-cm. hole.
4—Three layers of paper, middle layer perforated with five 0.58-cm. holes located at the corners and center of a 6-cm. square.
5—Three layers of paper, middle layer perforated with fifty-one 0.58-cm. holes arranged at the corners of 1.4-cm. squares.

raised to the point where a maximum power factor was obtained, but the curves show a corona formation for the thicker air space at a lower potential gradient. Curve 4 was obtained by placing upon the lower sheet of paper a second sheet having a hole 7.7 cm. in diameter. Upon this second sheet was placed symmetrically a brass disc about 10 cm. in diameter. In this way a confined air space 0.021 cm. thick was formed. The characteristics of this curve are not different from what had been obtained with the unconfined air space.

The curves in Fig. 13 were also obtained with the manilla paper impregnated with petroleum jelly. Curve 1 was for three layers closely pressed together by a one half-ton press. The curve shows that all air spaces were not eliminated. Curve 12 shows the results for a 7.7-cm. hole in the central part of the middle sheet. Curve 3 is for a hole 0.58 cm. in diameter in the middle sheet. The curve shows but slight difference to that for the three whole layers, indicating that the air spaces in the latter were comparable in effect with the air space intentionally formed. Curve 4 was obtained with five holes of the same size grouped near the center of the space beneath the upper electrode. Curve 5 was obtained with fifty-one holes of the same size laid out in regular pattern in the middle sheet between the electrodes. This curve does not differ greatly from Curve 2 for one large hole 7.7 cm. in diameter. In all these curves for the same thickness of dielectric, corona formation is indicated at the lower voltage for the greater area assuming the thickness of air space the same. Curve 5 which was carried to a higher potential gradient than Curve 2 shows a marked increase in power factor above 46 kv. per cm. This may have been due to heating as the voltage was in the neighborhood of breakdown.

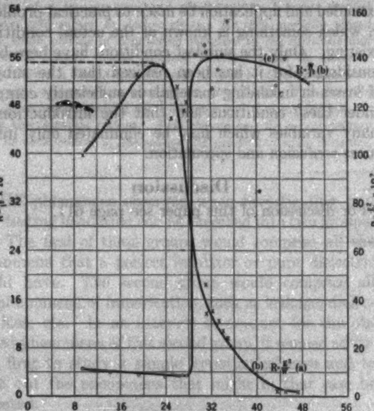

FIG. 14—CORONA IN AIR SPACES

60 Cycles

Manila paper impregnated with petroleum jelly.

Two layers of paper, one perforated with hole 7.7 cm. in diameter.

In the work referred to by Clark and Shanklin[1] they plotted effective resistance considered in parallel with the dielectric against potential gradient where they defined effective resistance by the expression $R_{eff} = \frac{E^2}{W}$ where E is the potential in volts and W is the watts loss. These investigators state that the characteristic form of curve is hard to obtain because of the exactness with which E is obtained, the square of which appears in the formula. If it is assumed that the effective resistance is in series with the test sample and the value of this quantity is obtained by the expression

$R_{eff} = \frac{W}{I^2}$ where W is the loss and I is the current

much more definite curves may be obtained though they are quite different. As an example, the data from which Curve 4, Fig. 12 was obtained were used to calculate the effective resistance by the two formulas. These are shown in curves *a* and *b*, Fig. 14. It is shown that the characteristic curve obtained by Clark and Shanklin, indicated by the dotted curve, is not obtained though no great trouble was taken to obtain very accurate values of E. This curve, however, is as near the form of the characteristic curve obtained by Clark and Shanklin as any which have been plotted by the writer. Curve *b* calculated by the formula

$R_{eff} = \frac{W}{I^2}$ is quite definite and shows quite sharply

the starting point of corona. Further the points below the starting point of corona are quite definite in comparison to those for the same data plotted in curve *a*. The points in the upper range of the Curve *b*, on the other hand, are not as definite as those in Curve *a*. The points in Curve *a* by the formula probably are indefinite more on the account of inaccuracy in the measurement of W than of E, since at low-potential gradients the losses are quite small and a large per cent of error may be made in measuring a very small quantity. Because the points are definitely determined for power factor, over the whole range of potential gradient, and since this plotting shows definitely the starting point of corona, the writer in this investigation chose this method of plotting results to show the starting point of corona caused by the ionization of air spaces in a dielectric.

In this paper so far, as well as in the paper by Clark and Shanklin, no attempt has been made to analyze the mechanism of the phenomena observed. No doubt the mathematical relations of the quantities involved could be worked out but that is outside the scope of the present paper. Physically, the relations shown in this paper may be expressed as follows: For any combination of air and a dielectric tested at low voltage, the losses should be in the dielectric, since the number of free ions in the air are small compared to the number in the dielectric. The losses in a good dielectric such as those used in these experiments should be in the nature of hysteresis losses rather than true ohmic losses, and would best be represented as a resistance in series with the dielectric. As the potential gradient is raised the free ions in the air space, though few in number at the start, soon acquire sufficient velocity to ionize other gas molecules in their path by the process known as ionization by collision. In this way, the ionized gas molecules are greatly multiplied until a point is reached where the characteristic discharge known as corona takes place. At this point the greater proportion of the losses occur in the air space and a large increase in current and losses are observed, the relation being such as to greatly increase the power factor. As the potential gradient is increased more ionization due to the increased velocity results and this produces greater losses and greater power factor. However, a point is reached in potential gradient where the greater proportion of gas is ionized so that further increase in potential gradient does not produce a corresponding increase in ionization. At this point then the change in the rate of increase of losses decreases and a lowering of the power factor is observed. According to this theory then these changes should be more pronounced with the thicker air space since the rate of multiplication of the ions is proportional to the distance they travel in the air space. This is in agreement with the observed results. With a thin air space, the free ions do not acquire a sufficient velocity to produce other ions in their path, hence corona is not observed at as low a potential gradient as for a thicker air space. Hence for a thin air space a higher potential corresponding to a higher velocity of the ions is necessary for corona formation, as has been shown in this investigation.

It is realized that the scope of this work may be extended and application be made to practical problems in which something is known of the actual conditions existing. Only the simplest conditions have here been considered, for it has been realized that the subject of losses in insulating materials is sufficiently complex under these conditions and that the introduction of many variables which may be eliminated only introduces confusion and speculation.

Discussion

For discussion of this paper see page 611.

The Action and Effect of Moisture in a Dielectric Field

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***Review of the Subject.**—In studying the subject of dielectric loss in electric cables the author has become convinced that the moisture content of the dielectric is the dominant factor determining the a-c. resistance. Evershead's explanation of the action of moisture in a fibrous dielectric seems plausible but leads to the conclusion that moisture causes a decrease of a-c. resistance with increasing voltage, whereas the experience of the author is that with a fairly well dried dielectric a-c. resistance is independent of voltage, and that decreasing the moisture content still further gives higher and higher a-c. resistance, with no limit in sight. It seems obvious, therefore, that Evershead has not fully covered the subject. In order to get a picture of the action of moisture in a dielectric field the author has assumed a simply hypothetical case and tried to follow it to its logical conclusions. He assumed a pure dielectric of a homogeneous and plastic nature between parallel electrodes and subject to electric stress. He then mentally placed a very small globule of conducting moisture in the dielectric and watched the action. Under constant potential stress the moisture elongated into a thread-like filament until it bridged the dielectric. But under alternating stress the moisture globule, if sufficiently small stretched out only a short distance and then no further, no matter how high the voltage. This showed how the a-c. resistance could be independent of the voltage and yet depend upon moisture.*

Following up the analysis the author was surprised to find that such a dielectric, containing particles of moisture would show absorption and residual charge and many other characteristics of actual insulation. He also found that certain unusual test data, obtained while testing cables, could be explained as due to a breaking up of the moisture filaments by evaporation. The author does not claim that the paper that follows meets the complexity of actual insulation, but rather that it adds to our conception of the importance of moisture in its effect upon a dielectric field.

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Alternating Field. (1500 w.)
Dielectric Loss as a Function of Voltage. (260 w.)
Dielectric Loss as a Function of Temperature. (340 w.)
Dielectric Loss as a Function of Frequency. (160 w.)
Capacitance as a Function of Frequency. (125 w.)
Capacitance as a Function of Temperature. (360 w.)
Phase Difference and Power Factor as Functions of Voltage Temperature and Frequency. (725 w.)
Appendix. (725 w.)

THE phenomena observed when investigating and testing insulation can be classified into two groups. The first of these groups would comprise all the phenomena that a perfect insulator or pure dielectric would have. The second group would comprise all the phenomena of imperfection, such as leakage, dielectric loss, etc. In an attempt to account for the observed phenomena of this second group, it seemed advisable first to study a simple hypothetical case and to trace out the phenomena that might in that case be expected.

The case chosen was that of a pure dielectric between parallel plate electrodes and containing, embedded in it, minute particles of conducting moisture. The case was considered both with constant potential and alternating potential across the electrodes and with variations of voltage, temperature and frequency.

It is not claimed that the analysis that follows is complete, as a complete mathematical treatment would be extremely complex. The analysis shows, however, that a dielectric with many particles of moisture embedded would have all the characteristic phenomena actually found in insulation. The inference is, therefore, that all of these phenomena, of the second group, can be explained as due to the presence of moisture in the insulation.

CONSTANT POTENTIAL FIELD

Consider first the forces that would act upon any single one of many particles of conducting moisture in a dielectric field with constant potential across the electrodes. Obviously if such a particle elongated into a filament of moisture, stretching in the direction of the dielectric field, it would reduce the energy of the field by shortening dielectric flux lines. It follows that a dielectric force would act upon the particle to produce such an elongation. We may designate this force as F_1

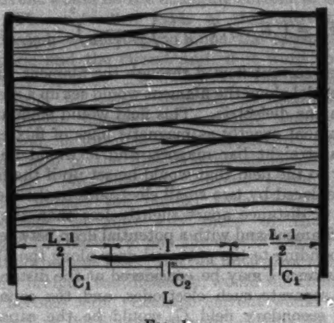

FIG. 1

$$F_1 = \frac{E^2 \, d \, C_1}{d\,(L - l)} \tag{1}$$

where C_1 is the capacitance between an end of the filament and the nearest electrode and E_1 the voltage

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across this capacitance. L and l are the length of the dielectric and the length of the filament respectively, as shown in the diagram, Fig. 1.

C_1 and $\frac{d\,C_1}{d\,(L-l)}$ can hardly be expressed mathematically as they depend not only upon the dimensions of the single moisture particle or filament considered, but also upon the dimensions and arrangement of the other moisture particles and filaments in the dielectric.

As the filament elongated l would increase and C_1 would increase, increasing F_1, but as C_1, increased, and the filament included more and more lines of dielectric force, a current would flow through the filament and this current, flowing through the resistance of the filament, would produce a potential drop along the filament E_2. F_1 can therefore be expressed as

$$F_1 = (E - E_2/2)^2 \frac{d\,C_1}{d\,(L-l)} \tag{2}$$

E_2 would be a function of the rate of change of l with respect to time and also of the resistance of the filament. Since the volume of moisture does not change, we may assume for the resistance of the filament $R = \frac{l^2}{\gamma A}$ where γ represents the conductivity of the liquid and A the section of the filament when $l = 1$. A also is the volume of moisture of the particle. We may therefore write

$$E_2 = f_1\left(\frac{d\,l}{d\,t}\right) \times \frac{l^2}{\gamma A} \tag{3}$$

and

$$F_1 = \left(E - f_1\left(\frac{d\,l}{d\,t}\right)\frac{l^2}{2\,\gamma\,A}\right)^2 \frac{d\,C_1}{d\,(L-l)} \tag{4}$$

When current flowed through the filament, the drop of potential along the filament would set up a secondary field in the dielectric. This field would emanate from the filament exactly as magnetic lines of flux emanate from a straight bar magnet, and it would be nearly similar to the field that would be set up if the filament were replaced by two small electrodes in the dielectric, spaced a distance apart slightly less than the length of the filament and with a potential drop between them corresponding to the potential drop along the filament. The distance l may be considered as the distance that would separate such electrodes, and the capacitance of the secondary field C_2 would be the capacitance between such electrodes.

This secondary field would act to shorten the filament and the force of this field would be

$$F_2 = -\frac{E_2^2\,d\,C_2}{2\,d\,l} \tag{5}$$

or by equation (3)

$$F_2 = -\left(f_1\left(\frac{d\,l}{d\,t}\right) \times \frac{l^2}{\gamma A}\right)^2 \frac{d\,C_2}{2\,d\,l} \tag{6}$$

The actual dielectric field would at any instant be a resultant field of what are here called the primary and secondary fields.

As the filament elongated friction would act to retard the elongation. This force of friction would increase as the filament attenuated and would depend upon the section of the filament, upon the nature of the dielectric and upon the rate of flow; it can be expressed as

$$F_3 = -f_2\left(\frac{d\,l}{dt}\,l/A\right) \tag{7}$$

Surface tension would also act upon the filament to contract it. If we assume that the force of surface tension

$$F_4 = -K\frac{d\,s}{d\,l}$$

where S is the surface of the filament, we may write

$$F_4 = -K\frac{\sqrt{\pi A}}{\sqrt{l}} \tag{8}$$

Considering all of the above forces as acting upon the filament we can write, for an elongation $\frac{d\,l}{d\,t}$

$$\left(E - f_1\left(\frac{d\,l}{d\,t}\right)\frac{l^2}{2\,\gamma\,A}\right)^2 \frac{d\,C_1}{d\,(L-l)} - \left(f_1\left(\frac{d\,l}{d\,t}\right)\frac{l^2}{\gamma\,A}\right)^2 \frac{d\,C_2}{2\,d\,l} - f_2\left(\frac{d\,l}{d\,t}\,l/A\right) - \frac{K\sqrt{\pi A}}{\sqrt{l}} = 0 \tag{9}$$

The relation $\frac{d\,l}{d\,t}$ to the other factors is obviously very complex but certain useful relations can be deduced from this equation by inspection.

It is obvious that if either A or γ is increased $\frac{d\,l}{d\,t}$ will also increase. In other words a large particle of moisture will elongate more rapidly than a small one. A moisture particle containing more impurity will elongate more rapidly than one with less impurity, and, since conductivity increases with temperature, a hot moisture particle will elongate more rapidly than a cold one. It also seems to show that if A is small $\frac{d\,l}{d\,t}$ decreases rapidly as l increases.

Forces F_2 and F_3 tend to slow down the elongation but can not stop the filament from elongating. Force F_4 would decrease as l increased. It would seem then that no matter how small the filament became, it would ultimately bridge the dielectric—even if it became atomic in section.

When the filament finally bridged the dielectric, the forces F_1 and F_3 would disappear, but the filament would now carry leakage current and would assume a gradient equal to the dielectric gradient. The dielectric field due to the potential drop along the filament would, therefore, remain, and the forces F_3 and F_4 would remain. These forces would hold the filament taut, but could not disrupt it or pull it away from the electrodes, for, if at any place along the filament the filament became thin, preparatory to a break, the resistance of that section would increase and the voltage gradient along that section would also increase. The resulting dielectric field would exert a force along the filament that would tend to flood the thin section in the filament with moisture from the thicker sections.

The filament would carry current electrolytically, that is, current would flow by migration of ions, and if the temperature of the liquid increased the velocity of migration would increase and possibly the degree of ionization would also increase. It follows that the leakage current would be greater if the dielectric were hot than if it were cold.

With current flowing in the filament, heat would be generated along the filament and this would increase the temperature of the filament and thus increase its conductivity. With increased conductivity the heat generated would increase and the temperature become still higher. This would result in a vicious circle, were it not for the fact that heat conduction to the surrounding dielectric would also increase with increasing difference of temperature between the filament and the dielectric, so that a condition of equilibrium would usually be reached. With a very small filament the ratio of heat generated to cooling surface would be small and such a filament would remain very close to dielectric temperature. Such a filament would show a resistance practically independent of the voltage between electrodes. If, however, the filament were large, we might expect resistance to decrease as voltage between electrodes increased.

If the temperature of the filament became sufficiently high, evaporation would occur, disrupting the filament. Evaporation might result in a general drying up of the filament, the moisture either leaving the dielectric or else forming a new filament or filaments in the dielectric adjacent to the original filament. Another possibility would be that the evaporation, being greatest at some one point, the resistance of that point would increase. The point would then become a hot spot and evaporation would further increase—a vicious circle ending in a local disrupture of the filament and a pushing apart of the sections by the resulting puff of vapor. This would decrease the flow of current and consequently the vapor would at once condense and the filament would be reunited, not only by the dielectric forces appearing across the gap in the filament, but also due to the vacuum when the vapor condensed. As soon as the sections of the filament united, in fact as soon as the ends touched, the action would be repeated—but the average conductivity would be reduced. With very large filaments evaporation might prevent any stable bridging of the dielectric.

The voltage at which evaporation first occurred would depend upon the size and conductivity of the filament. The larger the filament and the better its conductivity the lower the voltage of evaporation.

The voltage at which evaporation first occurred would also depend upon the temperature of the dielectric. The higher that temperature the lower would be the voltage of evaporation.

If a dielectric contained many particles of moisture, each of these particles would start elongating into filaments, but if the number of particles were great many of them would link up as they formed. This of course would decrease the time necessary to bridge the dielectric. Since, then, the time to bridge the dielectric depends both upon the number of particles and upon their size, it follows that the greater the moisture content of the dielectric the smaller the time required for the filaments to bridge the dielectric.

If a bridge were formed by the linking up of filaments as they elongated from particles of moisture of different sizes and conductivities, the voltage gradient across the bridge would not, at first, be uniform but the dielectric stresses set up along the filament, due to the gradient, would be greatest where the filament was highest in resistance. The result would be that an internal flow of moisture would occur until the gradient was uniform throughout.

If a dielectric containing many particles of moisture had voltage, from a source of constant potential, suddenly applied across the electrodes, the first rush of current would be the changing current of the dielectric. The maximum value of this current and its attenuation would depend upon the constants of the dielectric and the circuit and, if it were not for the moisture held by the dielectric, this current would soon drop to zero. However, as soon as voltage was applied, filaments of moisture would begin to form and, in forming, would apparently increase the capacitance of the dielectric by shortening the lines of force. The changing current would, therefore, persist beyond the normal time though gradually decreasing, as more and more of the filaments bridged the dielectric and the rate of change in length of others became less. But not until all of the filaments finally bridged the dielectric, would the changing current become zero. Leakage current would at first be zero but, as the filaments began bridging the dielectric, leakage current would increase. This increase in leakage current would at first be rapid, as the larger filaments and the filaments that linked up easily formed their bridges, but as the rate of bridging and the size of the filament that bridged became smaller and smaller the increase in leakage would become slower. Leakage would become maximum as changing current became zero. The action is shown diagrammatically in Fig. 2.

If the moisture content of the dielectric were great the action in building out filaments would be rapid and the leakage large. In that case as shown diagrammatically in Fig. 3 the current would reach its final value very soon after the application of voltage.

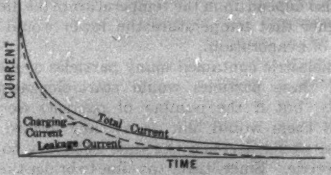

Fig. 2—"Absorption" Moisture Content Small

The phenomenon illustrated in Figs. 2 and 3 is apparently identical with what is usually called "absorption."

If a dielectric under electric stress, and bridged by filaments of moisture, were discharged by short circuit, the primary field of force would disappear at a rate depending upon the resistance and inductance of the discharge circuit, but, as pointed out above, a filament carrying current would have established along it in the dielectric a secondary field, proportional to the drop of potential along the filament. When the primary field disappeared this secondary field would become apparent and its discharge would be limited by the high resistance of the filament and, therefore, might be very slow. If Fig. 4 shows the normal gradient and flow of current along a filament under constant conditions in a changed dielectric field, the change in this gradient and current flow upon short-circuiting the electrodes would be as shown in Fig. 5.

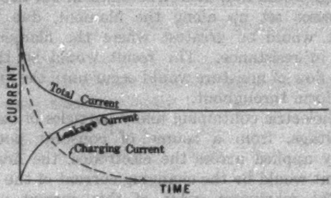

Fig. 3—"Absorption" Moisture Content Large

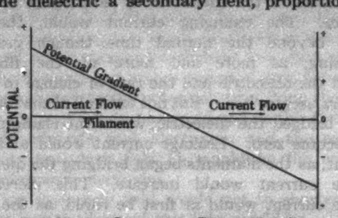
POTENTIAL
Potential Gradient
Current Flow
Current Flow
Filament
+
0
-

Fig. 4—Normal Gradient—Dielectric Charged

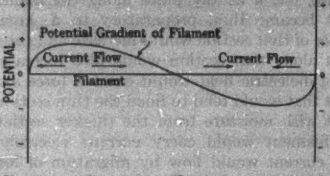
POTENTIAL
Potential Gradient of Filament
Current Flow
Current Flow
Filament
+
0
-

Fig. 5—Filament Gradient—Electrodes Short-Circuited

If left short-circuited long enough, the secondary field would become fully discharged and the gradient would disappear, but if, before that, the short circuit were removed the primary field would become reestablished by the secondary fields of all the filaments, as shown in Fig. 6 and 7.

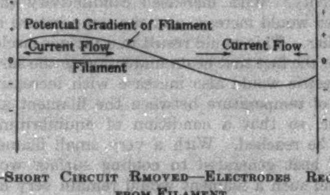
Potential Gradient of Filament
Current Flow
Current Flow
Filament
+
0
-

Fig. 6—Short Circuit Rmoved—Electrodes Recharging from Filament

The phenomenon illustrated in Figs. 4, 5, 6, and 7 is apparently identical with what is usually called "residual charge."

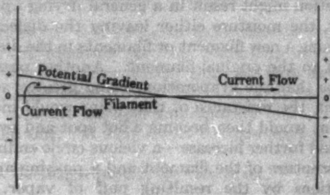
Potential Gradient
Current Flow
Current Flow
Filament
+
0
-

Fig. 7—"Residual Charge"

Discharge of the residual voltage would take place by leakage through the filaments until finally all difference of potential disappeared. When that occurred the force of surface tension would contract the filaments, but in contracting they would break up into small particles distributed along the paths of the filaments.

ALTERNATING FIELD

As in the case of the constant-potential field already considered, particles of moisture embedded in an alternating dielectric field would be acted upon by four forces: F_1, a dielectric force acting to elongate them into filaments and due to the primary dielectric field; F_2, a contracting force due to secondary dielectric fields set up by the potential drop along a filaments; F_3, surface tension; F_4, friction.

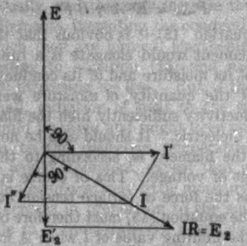

FIG. 8

The alternating field case is, however, rather more complicated than the other, because currents flow through the filaments whether the filaments are elongating or not. Thus, force F_2 is now not merely in the nature of a retarding force but acts to oppose force F_1 even if the filament is not elongating. Forces F_1 and F_2 are pulsating and not in phase.

To analyze the action, consider one filament of moisture, of many, in an alternating dielectric field. Alternating current I (see Fig. 8) would flow in the filament and this current can be considered as the resultant of two currents I' and I'', the first I' due directly to the main field, and proportional to the number of lines of force of that field entering the filament. This current would lead the electrode voltage E by 90 deg. I'', the second component of I is a current due to the secondary field set up in the dielectric by the voltage drop $I\,R$ along the filament. $I\,R$ is in phase with I and I'' leads this phase by 90 deg. It follows that E_2 leads E by more than 90 deg., and E_2 may be divided into two components, one of which E_2' is 180 deg. in phase from E. E_2', therefore, lessens the dielectric flux received by the filament and therefore lessens the force acting to elongate the filament. I of course, is proportional to the actual dielectric flux received.

The force F_1 would have a wave of double frequency and may be considered all positive. Its maximum values would occur when E was at full value either positive or negative. The force F_2 would also be of double frequency, and may be considered entirely negative. Its maximum values would occur when E_2 was at full value either positive or negative. The combination of these two forces would give a wave of force with both positive and negative values and with an intermediate phase. Due to friction, which in a small filament would be high, the filament could not respond to the rapid variation of the force cycles but would respond to the average resultant force F', of the force cycles of F_1 and F_2. If F' were positive in direction and exceeded the surface tension force F_3, the filament would continue to elongate, but elongation would cease if the forces F' and F_3 became equal and opposite in direction.

As the filament elongated its resistance would increase and, assuming that the total volume of moisture did not change, the resistance of the filament would increase in proportion to the square of its length. Although the current I might decrease as the filament lengthened, the voltage drop along the filament would be found to increase, and this would increase the force F_2. It would also swing the phase of the voltage E_2 further in advance of E and increase the component E_2' thus decreasing the force F_1. When the attenuation of the filament reached a certain degree the forces acting upon it would be in equilibrium and no further elongation would take place.

To show this a little more definitely it is convenient to consider the case from an energy standpoint, as all bodies, either conductors or insulators, in a dielectric field, tend to move or form themselves so as to take the maximum possible energy from the field. Thus if by elongating the energy loss in a filament would become greater, dielectric forces would tend to elongate the filament but the filament would not elongate if elongation meant a decrease of energy. The heat produced in the filament is a measure of the energy it takes from the field.

In Fig. 9, Let

$$1/r = g \qquad 2\,\pi\,f\,C_1 = b_1 \qquad 2\,\pi\,f\,C_2 = b_2$$

The admittance of the parallel circuit would be $y_2 = \sqrt{g^2 + b_2^2}$ and the impedance of the total circuit would be

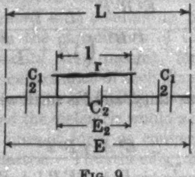

FIG. 9

$$z = \sqrt{\left(\frac{g}{g^2 + b_2^2}\right)^2 + \left(1/b_1 + \frac{b_2}{g^2 + b_2^2}\right)^2} \qquad (10)$$

It follows that since

$$E_2 = \frac{E_1}{y_2\,z}$$

and power loss in heating the filament $P = E_2^2\,g$

that
$$P = \frac{E^2 g}{\frac{g^2 + b_2^2}{b_1^2} + 2\,\frac{b_2}{b_1} + 1} \tag{11}$$

As the filament lengthened out and l increased g, b_1 and b_2 would change in value

$$g = \frac{A\,\gamma}{l^2}$$

where γ is the conductivity of the liquid and A the sectional area at unit length, which equals of course the volume of the liquid

$$\frac{d\,b_1}{d\,l} \quad \text{and} \quad \frac{d\,b_2}{d\,l}$$

are actually rather complicated functions of L and l; and b_1 does not increase as rapidly as $L - l$ decreases, nor does b_2 decrease as rapidly as l increases, but if a value of l can be found giving P a maximum value on the assumption of direct proportionality it may be inferred that at some shorter value of l the filament would attain its maximum length.

Assume therefore $\quad b_1 = \dfrac{B\,F}{L - l}$

and $\quad b_2 = B/l$

when B is the value of b_2 when the filament is of unit length and F a factor of proportionality between the two fields.

The equation can now be written

$$P = \frac{\frac{E^2 A\,\gamma}{l^2}}{\frac{\frac{A^2\,\gamma^2}{l^4} + B^2/l^2}{\frac{B^2\,F^2}{(L-l)^2}} + 2\,\frac{B\,(L-l)}{l\,B\,F} + 1} \tag{12}$$

which reduces to

$$P = \frac{E^2\,B^2\,F^2\,\frac{l^2}{(L-l)^2}}{A\,\gamma + \frac{l^4\,B^2}{A\,\gamma}\left(1/l + \frac{F}{L-l}\right)^2} \tag{13}$$

If L is taken as unity, and l is small with respect to L this reduces to

$$P = \frac{E^2\,A\,\gamma\,B^2\,F^2}{\frac{A^2\,\gamma^2}{l^2} + B + 2\,F\,B\,l + B\,F^2\,l^2} \tag{14}$$

Differentiating this with respect to l and equating to zero gives

$$A^2\,\gamma^2 - F\,B\,l^3\,(1 + F\,l) = 0$$

F will not be a very large number and if l is small $\times\, l + F\,l$ can be considered unity and we may write

$$l_{max} = \left(\frac{A^2\,\gamma^2}{B\,F}\right)^{1/3} \tag{15}$$

Obviously for small values of l, $B\,F$ must be greater than $A^2\,\gamma^2$.

Now putting this value of l in equation (14) gives

$$P_{max} = \frac{E^2\,A\,\gamma\,B^2\,F^2}{3\,A^{2/3}\,\gamma^{2/3}\,B^{2/3} + B + B^{1/3}\,F^{4/3}\,A^{4/3}\,\gamma^{4/3}} \tag{16}$$

and if $B\,F$ is to be large with respect to $A^2\,\gamma^2$ the term B will dominate the denominator and we can approximate the above formula by

$$P_{max} = E^2\,A\,\gamma\,B\,F^2 \tag{17}$$

From equation (15) it is obvious that the length to which a filament would elongate is a function of the quantity of its moisture and of its conductivity. Presumably if the quantity of moisture were sufficient or its conductivity sufficiently high the filament would bridge the dielectric. It should also be noted that the length of the filament is, according to this equation, independent of voltage. This of course is not strictly the case, as the force of surface tension has been neglected. The equation (15) must therefore be considered as giving the limiting value of l when A is very small. Undoubtedly for small voltages the effect of surface tension would be apparent but as the voltage increased the dielectric forces would dominate, and if γ remained constant the length of the filament would not change appreciably with voltage changes.

Equation (17) is the approximate equation of dielectric loss due to the presence of a very short filament of moisture in the dielectric but for larger filaments equation (17) will not hold. Most likely as l increased the factor B should decrease in importance until for a filament of length such as to bridge the dielectric the factor B would disappear and the loss would be

$$P = E^2\,A\,\gamma \tag{18}$$

where $\dfrac{1}{A\,\gamma}$ expressed the actual resistance of the filament, since we assumed the dielectric thickness, L, to be unity.

If the dielectric contained many particles of moisture of various sizes, doubtless some would bridge the dielectric, some would not elongate beyond a limiting or short value and some in elongating would link up with others forming longer filaments of limited length or else would bridge the dielectric.

With some filaments bridging the dielectric and others of limited length the total dielectric loss can be expressed as

$$P = E^2\,\gamma \int_{l=0}^{l=L} A'\,B'\,d\,l \tag{19}$$

where A' is a function of A and l and expresses, for any length l, the total moisture in the dielectric, held as filaments, of length l, B' is a function of B and F with respect to l and varies from $B' = B\,F^2$ for very small values of l, to $B' = 1$ for $l = L$. B is also a function of l and would be 0 for $l = 0$. In this equation γ is assumed to be the same in all filaments but if the filaments were of different temperature this would not be the case.

DIELECTRIC LOSS AS A FUNCTION OF VOLTAGE

According to equation (**19**) the dielectric loss in a dielectric containing moisture increases as the square of the voltage indicating a constant "a-c. resistance" but as pointed out in the case of the constant potential field, the current flowing through the filaments generates heat, locally, and this may increase the temperature of the filaments, increasing the conductivity of the liquid of which they are formed, lengthening the filaments according to equation (**15**) and according to equation (**19**) increasing the loss. But, if the filaments are very small, radiation of heat to the surrounding dielectric would be rapid and might even cool the filaments down to the dielectric temperature between cycles. We would, therefore, expect that in a dielectric containing comparatively little moisture, dielectric loss would increase in proportion to the square of the voltage while in a comparatively moist dielectric the increase of dielectric loss with voltage would be at a greater rate. The phenomena of evaporation as explained in the case of the constant potential field would also occur in an alternating field and this might offset the increase in conductivity due to temperature rise as voltage increased. The evaporation, however, would only be apparent above some critical voltage. In other words, a dielectric containing moisture to such an extent as to increase in loss, as voltage increased, at a rate greater than proportional to the square of the voltage, would, above a certain voltage, show loss increasing at a rate more nearly proportional to the square of the voltage.

DIELECTRIC LOSS AS A FUNCTION OF TEMPERATURE

Assuming for the moment that the dielectric coefficient, k, is independent of temperature, then since γ, the conductivity of the liquid increases as temperature increases, it follows from equation (**19**) that the dielectric loss in a dielectric containing many particles of moisture would increase as the temperature of the dielectric increased. Furthermore as indicated by equation (**15**) an increase in γ would also cause a lengthening of all the filaments that did not already bridge the dielectric, and according to equation (**19**) this would cause a still greater increase of dielectric loss as temperature increased.

There seems, however, to be rather good evidence that the dielectric coefficient, k, is not a constant with respect to temperature. This will be brought out later, but assume for the moment that k decreases as temperature increases. B is proportional to k and so according to equation (**19**) a change in k will affect dielectric loss. In a comparatively dry dielectric a large part of the loss might occur in comparatively short filaments in which case the importance of B in the equation (**19**) for loss would be great. In such a dielectric the effect of the increase of conductivity as temperature increased might be somewhat offset by the decrease in k as temperature increased, though, as the filaments lengthened due to increasing temperature the importance of B as affecting loss would decrease. The result, in a very dry dielectric, might be that, when cold, dielectric loss would decrease as temperature increased but that, at a certain temperature, a point of minimum loss would be reached and that, for higher temperatures, loss would increase perhaps rapidly with temperature.

It has been stated above that dielectric loss is sometimes affected by evaporation, depending upon the moisture content and the voltage impressed. Another factor would be the dielectric temperature, for obviously if the dielectric were hot evaporation would occur at a lower voltage than if the dielectric were cold.

DIELECTRIC LOSS AS A FUNCTION OF FREQUENCY

If a filament of moisture in a dielectric field were very short the importance of B as affecting dielectric loss would be great. B is proportional to frequency so the loss would be nearly proportional to frequency. If, on the other hand, the filament bridged the dielectric, the loss would be independent of frequency. In the case of many filaments of all sizes, dielectric loss would increase with frequency but in a degree depending upon the quantity of moisture and its distribution.

As an offset to the above is the fact that, as indicated in equation (**15**), the length of the filaments would decrease as frequency increased. This of course though tending to decrease dielectric loss would increase the importance of B and so increase the sensitiveness to changes in frequency.

With an increase of temperature, the variation of loss, due to changes in frequency, would be less as the increase of temperature would lengthen the filaments, and so give less importance to B.

CAPACITANCE AS A FUNCTION OF FREQUENCY

The capacitance of a dielectric containing embedded moisture elongated into conducting filaments would be greater than the capacitance of the same dielectric if no filaments were present, for although the effect upon the capacitance of such filaments as bridged the dielectric would be negligible, those filaments that partially bridged the dielectric would act to shorten the length of such lines of force as converged to them in crossing the dielectric. Thus the effect of these filaments would be the same as if the electrodes were moved nearer together. An increase in frequency would increase the factor B in equation (**15**) and shorten the length of these filaments; thus an increase in frequency should be accompanied by an apparent decrease in capacitance.

CAPACITANCE AS A FUNCTION OF TEMPERATURE

As pointed out above, the effect of an increase of temperature upon the filaments that do not bridge the dielectric, is to increase their conductivity and so increase their length. Obviously, this would increase the apparent capacity of the dielectric. But as stated above there is no reason to assume that the dielectric coefficient k is independent of temperature. It is a measure of the energy required to produce some atomic change, and the condition of an atom changes with temperature.

W. Grover[1] of the Bureau of Standards has found that the capacitance of paraffined paper condensers changes with temperature but with rather a complex relation to phase angle. It will be shown later that in the dielectric we are considering the larger the phase angle the greater the moisture content. Grover finds that, for a very small phase angle, the capacitance decreases as temperature increases—for a larger phase angle capacitance is nearly independent of temperature and for a still larger phase angle capacitance increases as temperature increases. A very small phase angle is equivalent to saying very few filaments and these of short length. Such filaments, although they would, presumably, increase in length as temperature increased, would, in lengthening increase the capacitance of the dielectric but slightly. If in this case the capacitance were found to decrease with an increasing temperature our only explanation seems to be that a decrease of k must have taken place. A larger phase angle would indicate more moisture, that is more filaments and longer filaments. When due to an increase of temperature, such filaments elongated, their effect upon capacitance would be more pronounced and might dominate over any change due to a change in k. It follows that when investigating k as a function of temperature, the moisture content should be as small as possible; in other words the phase angle should be small. In this case Grover found that capacitance decreased as temperature increased. The conclusion seems to be that the dielectric constant k actually does decrease as temperature increases.

PHASE DIFFERENCE AND POWER FACTOR AS FUNCTIONS OF VOLTAGE TEMPERATURE AND FREQUENCY

The phase angle of the changing current of a condenser would be

$$\tan^{-1}\theta = \frac{b}{g} = r_{ac}\,2\,\pi\,f\,C$$

if however the phase angle is large we can assume for the power factor

$$\cos\theta = \frac{1}{r_{ac}\,2\,\pi\,f\,C}$$

and since $r_{ac} = \dfrac{E^2}{P}$ $\cos\theta = \dfrac{P}{E^2\,2\,\pi\,f\,C}$

The term "phase difference" may be defined as 90 deg. $-\ \theta$.

The dielectric loss P and capacitance C have both been analyzed above as functions of voltage, temperature, frequency and moisture content, and as these are the only variables in the equation of power factor that would be influenced by moisture content it seems hardly necessary to fully develop their ratio. In general we might expect P to change more with moisture content and conductivity of the moisture than C and it would follow that in a comparatively dry dielectric, power factor would be lower and phase difference smaller than in a comparatively moist dielectric.

In any actual insulation the action of entrapped moisture would be more complex than in the simple case considered above. It is doubtful however if any usual insulation would be dense enough to prevent the penetration of filaments of moisture provided the filaments were sufficiently small, and they may of course be even atomic in section. The impossibility of freeing insulation from every trace of moisture is apparent when we consider the moisture content of the air. If we attempt to drive out moisture by high temperature we vaporize the moisture but even with vacuum we cannot get all of the vapor out. There seems to be an action of occlusion that holds to the moisture and brings in new moisture when possible from the air. If very high temperatures are used in drying, many insulations decompose and usually one of the products of decomposition is water.

The idea that moisture forms the conducting paths in insulation is not at all new, Evershead[2], by means of a very ingenious model studied the action of moisture as affecting the insulation resistance of fibrous insulating materials. This is of course a more complex case than the simple one considered above, since the fibers of the material would hold moisture strongly by capillary action. Evershead concludes that only a small part of the total moisture forms high resistance paths and that most of the moisture lies dormant in cells and fibers of the insulation. According to Evershead, an increase of electrical stress floods the conducting paths with moisture taken from the reservoirs of dormant moisture and so decreases the resistance as voltage increases. Evershead accounts for this flooding of the moisture paths by the action of electrical endosmose which gives a movement towards the cathode only. Electrical endosmose is essentially a phenomenon of a dielectric liquid and not of a conducting liquid, and it hardly seems possible that moisture in commercial insulation would be pure enough to be considered as a dielectric. Conducting moisture on the other hand would elongate into filaments, the force acting in both directions, both towards anode and cathode. Possibly both actions may take place.

In the above analysis we have considered only the actions that would take place, due to moisture, in a uniform dielectric field. If the field were not uniform, as for instance in the insulation of an electric cable, it seems obvious that the moisture would have a tendency to migrate towards the more intensely stressed portions of the field. One result of this would be an easing off of the gradient where it was steepest. It may possibly be that an actual benefit is derived from the moisture in a cable if the potential gradient at the conductor is excessive.

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[1] The capacity and phase difference of paraffined paper condensers as functions of temperature and frequency. W. Grover, *Bulletin of the Bureau of Standards*, Vol. 7, No. 4, 1911.

[2] The Characteristics of Insulation Resistance. *Journal of the Institution of Electrical Engineers*, Dec. 15, 1913.

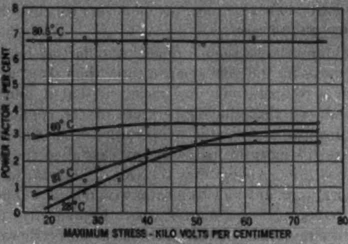

Fig. 10—Power Factor of the Charging Current
Single-phase, 60 cycles.
Single-conductor No. 0000, 20/32-in. paper cable.

Almost all of the characteristics that it was found should be expected in the hypothetical insulation that has been considered above have been described before as characteristics of ordinary insulation. Perhaps the characteristics described above as due to evaporation may be considered novel. Among many tests made on cables and other insulation, the author has occasionally found variations that it seemed probable were caused by evaporation. Such a test is given in the appendix.

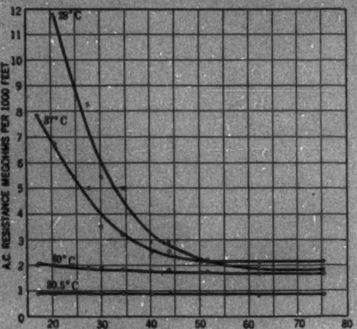

Fig. 11—A-C. Insulation Resistance
Single-phase, 60 cycles.
Single-conductor No. 0000, 20/32-in. paper cable.

Appendix

The curves shown in Figs. 10, 11 and 12 were plotted from dielectric loss measurements made upon a single conductor cable insulated with paper and impregnated with mineral oil. This was a special experimental length of 200 feet and it was given less drying than would have been given to a commercial cable of similar design. The curves plotted from the results of the test show the typical characteristics which we have learned to associate with insufficient drying. In a cable where the drying is more complete we find that dielectric loss is proportional to the square of the voltage and that, at any given temperature, power factor and insulation resistance do not change greatly as voltage changes. In this case, however it is only at high temperature that insulation resistance and power factor do not change with voltage. At low temperatures, insulation resistance decreases with increasing voltage and power factor increases with increasing voltage. The lower the temperature the greater the rate of change. But in each case if the voltage is sufficiently high a condition of constant insulation resistance and constant power factor is reached. The voltage to bring about this condition depends upon the temperature and is greater for low temperatures than for high.

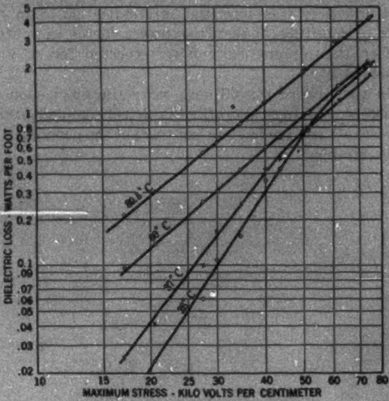

Fig. 12—Dielectric Loss
Single-phase, 60 cycles.
Single-conductor No. 0000, 20/32-in. paper cable.

The explanation for these curves according to the theory given in the above paper is as follows:

Many of the moisture paths or filaments of moisture are, in this case, so large that their surfaces, which dissipate heat, are small with respect to the heat generated in them by electric currents. The moisture therefore becomes hotter than the surrounding dielectric, the actual temperature depending upon both the dielectric temperature and the voltage. Therefore as voltage increases the temperature and conductivity of the moisture increases and the filaments of moisture lengthen. Due to both these causes, a-c. resistance decreases and power factor increases with increasing voltage. But if the temperature of these large filaments becomes sufficiently high, they will be disrupted by evaporation. The cooler the dielectric the greater must be the rise in temperature to reach an evaporating temperature. Therefore the cooler the dielectric the higher must be the voltage to produce evaporation. Evaporation breaks up the large filaments, thus changing the slope of the curves to the horizontal lines that are characteristic of comparatively dry dielectric, in which only small filaments are present.

In the case of the 80.5 deg. curves it would seem that the dissipating action of evaporation must have been complete well below the lowest voltage recorded in the test and that, therefore, the only indication of an excess of moisture is that the power factor is a little higher than might have been expected for a well dried cable.

In the case of the 60 deg. curve the dissipation of moisture, due to evaporation, is almost complete at the lowest test voltage but the last trace of the phenomenon is discernible.

The crossing of the 28 deg. and 37 deg. curves is interesting and apparently means that at 28 deg. a larger part of the total moisture was concentrated in the large filaments than at 37 deg. cent. so that, at the evaporating voltage, the moisture as a whole was hotter in the 28 deg. dielectric than in the case when the dielectric was 37 deg. The fact that at 28 deg. the oil is hard while at 37 deg. the oil is very soft may have bearing on the case.

At high voltages there is much less difference between the curves for different temperatures than there would be for a comparatively dry dielectric, but it must be remembered that the temperature of the conducting moisture paths is not the temperature of the dielectric, nor are the moisture paths in any case all at the same temperature. Above the voltage of dissipation by evaporation many moisture paths would be at evaporation temperature no matter what the dielectric temperature might be. Other paths in the dielectric would be at temperatures between the evaporation temperature and the dielectric temperature. Thus the 80.5 deg. cent. curves differ from the others at high voltage not because the hottest moisture is any hotter than in the other cases but because more moisture is hot.

Discussion

For discussion of this paper see page 611.

Rating of Cables in Relation to Voltage

Bibliography on Dielectrics

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THIS bibliography was prepared at the request of the Subcommittee on Wires and Cables of the Standards Committee of the Institute, and is intended specifically to be a continuation of that published by E. H. Rayner, *Journal of the Institution of Electrical Engineers*, (England) 1912, Volume 49, p. 53, who describes his bibliography as follows:

> The references given below are to articles in periodical literature only. With few exceptions they deal with the physics of dielectrics from the point of view of energy loss and electric strength.
>
> The first section includes papers dealing with theory and experiments of a laboratory nature.
>
> The second deals with instruments, chiefly electrostatic voltmeters and wattmeters, suitable for measurements on high-voltage circuits.
>
> The third section includes papers on atmospheric phenomena at high voltages at or above ordinary pressures, more especially such as describe experiments of engineering interest.
>
> In the fourth section are references to similar experiments in oils.
>
> The fifth section consists chiefly of papers dealing with the electric strength of materials and energy loss in insulation. Articles on cables are included which discuss insulation problems; but such as deal merely with capacity, inductance, etc., have been omitted.

The number of articles on the subject of porcelain and porcelain insulators has increased so much since the publication of Rayner's bibliography, that an additional Section, namely Section V, has been included on this subject in the present bibliography, changing the general section into Section VI.

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Discussion

RATING OF CABLES IN RELATION TO VOLTAGE HISTORICAL SUMMARY

(SUBCOMMITTEE ON WIRES AND CABLES OF STANDARDS COMMITTEE);

DIELECTRIC LOSSES AND STRESSES IN RELATION TO CABLE FAILURES (ROPER);

ON THE MINIMUM STRESS THEORY OF CABLE BREAK-DOWNS (SIMONS);

EFFECTS OF THE COMPOSITE STRUCTURE OF IMPREGNATED PAPER INSULATION ON ITS ELECTRIC PROPERTIES (DEL MAR AND HANSON);

POTENTIAL GRADIENT IN CABLES ((MIDDLETON, DAWES AND DAVIS);

CORONA IN AIR SPACES IN A DIELECTRIC (SHRADER);

ACTION AND EFFECT OF MOISTURE IN A DIELECTRIC FIELD (DU BOIS);

BIBLIOGRAPHY ON DIELECTRICS (SIMONS).

Niagara Falls, Ontario, June 29, 1922

E. B. Meyer: As already stated by one of the writers, the general opinion in the past seemed to be that when the voltage of a circuit was increased the only requirements so far as safe operation was concerned, was to add more insulation to the cable.

Recent experience and research has developed the fact that the quality of the insulation and of the compounds used for impregnation have an important bearing on the safe operation of underground cables.

The thickness of insulation applied on cables has apparently been determined heretofore by a cut and try method. In several installations with which I am familiar, cables recently purchased have less insulation applied than some of the older installations operating at the same voltage. This seems to bear out the fact that either more insulation than necessary was originally provided, or that improvements in the quality of dielectrics have been effected.

In the operation of underground cable systems of voltages under 9000 comparatively little trouble is experienced. However, as soon as we pass this point and get into the range of voltages close to 20,000 which is becoming more extensively used, the number of failures per unit length of cable show a large increase over the number experienced at lower voltages.

In looking over the last report of the Underground Systems Committee of the National Electric Light Association in which was included a record of the cable failures during the year 1921 on cable systems at voltages ranging from 6600 to 25,000 volts, it is interesting to note that the average number of cable failures excluding those caused by electrolysis or external injury on a total of nearly 5000 miles of cable was slightly over 10 failures per 100 miles.

In a large number of systems in this classification operating at voltages over 15,000 the failures ran about 25 failures per year per 100 miles of cable. It is really seen from these figures that in order to reach what might be termed the "ideal condition" as cited by Mr. Roper in which he states that the burnouts of high-voltage cables should be no larger than for the lower transmission voltages and should not exceed one or two per hundred miles per year, radical changes and improvements will be necessary both in the construction and methods of handling underground transmission cables of the higher voltage class.

F. W. Peek, Jr.: I will limit my discussion to the data by Fernie given in Table I of Mr. Simons' paper. These data were obtained by measuring the break-down voltage on cables with inner conductors of various radii. The maximum stress or gradient on the insulation of such a cable is always at the surface of the inner conductor; the minimum stress is at the sheath or outer cylinder. The stress or gradient calculated from the break-down voltage varies with the size of the inner conductor. The apparent strength of the insulation is greater for the smaller sizes of conductor. Exactly the same result is obtained with oil and air. The apparent strength of air for various sizes of conductors is readily obtained from the well established relation

$$g_v = 30 \left(1 + \frac{0.30}{\sqrt{r}} \right) \text{kv./cm.} \tag{1}$$

Where r is the radius of the conductor in cm.[1]

Data from Table I are given below with some additional calculations.

Data from Table I				Calculated from Equation (2)		g_v for air from equation (1)
R cm.	r cm.	Max. Stress at Cond. g_v kv/cm.	Stress at Sheath kv/cm.	Max. Stress at Cond. g_v kv/cm.	$R' = 1.1 \sqrt{r}$	
1.13	.243	428	92	320	0.8	48
1.79	.527	335	98.3	250	1.30	42
1.25	.369	288	84.3	280	1.00	45
1.41	.527	257	95.6	250	1.30	42
1.62	.737	240	108.7	240	1.70	40
1.16	.527	219	99.5	250	1.30	42
1.70	.817	189	90.6	220	1.80	41

In the last column the stress is calculated for the same conductor arrangement as for the cable for the purpose of comparison. The apparent strength is greater for the smaller conductors as is the case for this cable.

The physical meaning of equation (1) is that when breakdown occurs the stress is not constant at the conductor surface but is always constant and equal to 30 kv./cm. at $0.3 \sqrt{r}$ cm. from the conductor surface. This constant value of 30 kv./cm. is the strength of air, but a finite thickness must be stressed at or above this value before break-down can occur. This thickness is $0.3 \sqrt{r}$ cm.

The break-down values for the solid insulation from Table I may be represented by the same relation. Thus

$$g_v = 100 \left(1 + \frac{1.1}{\sqrt{r}} \right) \tag{2}$$

This means that the solid insulation breaks down at a constant stress of 100 kv./cm. at $1.1 \sqrt{r}$ cm. from the conductor surface. It so happens that the radii of the sheaths, R, for the cables used in Table I have values approximately equal to $1.1 \sqrt{r}$. This makes it appear that break-down occurs for a constant value of stress at the outer conductors.

C. F. Scott: I have some appreciation of cables, in a general way, I am not an expert, I am not going into this discussion in the way that the preceding persons have done.

I will look at the whole matter from a different standpoint, that is, with reference to the place of the cable in commercial engineering work. We see the large power houses which have been constructed—we marvel at the advance which has been made in the last twenty years, since turbines began to be factor in power generation, and yet, in the large cities, the investment in the cables which lie beneath the street, is comparable with the investment in the power houses, and the continuity of service may be as much dependent on cables as it is on the operating machinery of the power houses.

What do we find with regard to the change in cables in the last twenty years? It is about twenty years ago, if I recall rightly, that a cable of some 25,000 volts was installed, and so far as I know, has been reasonably successful and has been in continuous operation since that time. Yet, the number of cable installations, which have exceeded that voltage, have been very few and very recent, and neither in quantity or quality have they proved, I think, that they are yet 100 per cent perfect; and the one particular point I want to make is that the advance which has taken place in cables from the technical and operating standpoint, has been very mild and feeble, compared with that in other branches of the electrical industry.

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[1] Peek, "Dielectric Phenomena in High-Voltage Engineering", p. 47.

We had presented, a day or so ago, the fact that in telephonic transmissions, efficiencies equal to the older efficiencies were obtained with wires of 1/10 the size, and that this was accomplished with cables containing something like ten times the number of circuits that they used previously.

That immediately raises the question why power cables have changed so little. Has the cable not been something that has been turned out by the mile, according to very ordinary sort of specifications? Has not the type of work, as has been presented here this morning, which is the theoretical research type, been of very slow progress and has not the theory advanced too slowly? Has not the practical application of that theory and the results of the research work which has been done on cables, to make better cables, not been very slow? In a word, are we not ten to twenty years behind the times in the real advance in power cables, in comparison with what has been going on in other fields of the electrical industry?

If that is so, it is a challenge to the electrical profession, to the theoretical men, to the cable makers, to get very busy in order that the cable, may take its proper part in performing its very important function in power distribution.

C. F. Proos: In a paper read before the Association of Electrical Central Station Managers in Holland, on September 30th, 1921, (to which the following figure numbers refer) there were discussed certain factors that influence the dielectric loss in high-tension cables, with special reference to the tension at which ionization starts as influenced by changes of temperature.

The general characteristics of a paper insulated cable is shown in Fig. 1, where $\frac{W}{E^2}$ is given at different voltages. It will be noted that up to a certain value $\frac{W}{E^2}$ is constant; beyond that point $\frac{W}{E^2}$ changes due to the air becoming ionized; and at yet higher voltages it becomes nearly constant again, when the air is nearly totally ionized.

The time during which voltage is applied has influence on the measured value of dielectric loss, but only on the second part of the characteristic. Slow readings or low ionization give curves like No. III Fig. 5 instead of No. I.

Temperature has a large influence on dielectric loss as shown in Fig. 7. The curves show a minimum of losses, for all tensions, at nearly 37 deg. cent.

The ionization characteristic (Fig. 1) is changed by heating and cooling the cable. The ionization voltage runs up with temperature, and comes down, when the cable cools, to lower values than before. The higher the temperature reached, the lower the ionization voltage in the cooled cable, as shown in Fig. 9. There is a certain temperature of the heated cable, above which the ionization voltage in the cooled cable runs down rapidly (Fig. 10). Running the cable above this temperature makes the operating conditions dangerous, unless unusually thick insulation is used.

The power factor also changes with differences in temperature and is dependent on the range of temperature the cable has previously covered, as shown in Fig. 11.

In the original paper these results are discussed at length and it is shown that these changes in electrical values are caused and can be explained by the changes in volume and pressure of the small occluded air bubbles that are left in high-tension cables. Both the thickness and the pressure of the air bubbles change and ionization starts at different voltage in accordance with these changes. The expanding air pushes the fluid oil away at the spots of higher temperature which are also spots of highest dielectric loss and stress; these spots are dried out, the temperature rises and the resultant hot spot causes breakdown. The oil pushed away at high temperatures, does not come back to its former place when the cable has cooled down; the air occupies a bigger space than before, the pressure coming down accordingly. Hence at lower temperatures, the break-down voltage of the air bubbles is lower, and the heavy ionization which occurs is dangerous and may cause hot spots and consequent breakdown of the cable. Practise in Holland has confirmed this theory, several breakdowns having been noticed at the low temperatures which followed a period of heavy load on the distribution cables.

Ionization tension lowered by heavy loading of the cable comes back to former values in course of time. An average time for the recovery of a cable is 8 to 10 days. At higher temperatures recovery is faster. Curves taken on a recovering cable are shown in Fig. 12. It will be noticed from these curves, that the same cable can show nearly any possible form of characteristic according to the conditions (thermal and electrical) the cable has been subjected to before test. This explains most of the differences which have been experienced in checking dielectric loss measurements.

By special precautions taken in manufacture and in the materials used, the ionization stress in cables can be brought up to values of 40 kv./cm. or more and the influence of temperature changes can be reduced. (Figs. 14 to 19).

A cable always used at an operating voltage lower than the ionization voltage does not show hot spots; hot spots are caused by occluded air only, and will cause breakdowns sooner or later. Laboratory tests should be made on cooled cables after being heated up to operating temperatures. A proper knowledge of a cable's characteristics cannot be obtained unless its voltage characteristic is determined over a wide range of voltages. (Fig. 7). A test at one voltage only is insufficient; the ionization voltage must be known under all operating conditions.

The above tests were made at the Nedelandsche Kabelfabrik on lengths of 1000 feet or more with a special wattmeter at 50 kv./cm. The cables were heated by passing currents through the conductors, the sheaths being freely exposed to air. This is different from the American practise of putting cables in an oven until the insulation, is uniformly hot throughout, and more nearly represents operating conditions.

William A. Del Mar: In the course of preparing the Historical Summary, the Subcommittee noted that the first man to call attention to the importance of dielectric losses in cables was Mr. Philip Torchio. They found that in 1902 Mr. Torchio gave the results of measurements of dielectric losses on long feeder cables, and deduced the general laws which govern the variation of dielectric loss with voltage frequency and temperature.

Philip Torchio: Your reference to my work may be used as an illustration in answering Prof. Scott's very timely remarks which are more or less an attack on the slowness of American progress in cable development. As the Chairman states, I was the first to make tests and call attention to the importance of dielectric losses in cables in the Spring of 1902. My conclusions on the tests as I then reported were as broad and comprehensive and covering all features of the problem as we would enunciate them today, my report of 20 years ago stating that "the dielectric losses are approximately proportional to the frequency, to the square of the voltage and to a certain function of the temperature not yet determined. The temperature, however, increases considerably the dielectric losses."

I submit to Prof. Scott this fact, that while the fundamental principles of the importance of dielectric losses were clearly enunciated in 1902, practically nothing was done in this country in following up the subject until about 10 years afterwards when, in 1912, Mr. Roper was confronted with certain high-tension cable failures due to heating, and he then became persistent in urging that the study of dielectric losses in cables be seriously taken up and pushed forward. In later years, other operating engineers who experienced similar troubles vitally contributed to exert pressure to push the research. In this manner, through the efforts of both manufacturers and users either through independent or cooperative work, we have arrived at the large progress reported in these papers.

In reviewing these developments, I believe Prof. Scott will recognize the fact that until the need for improvements is felt either on account of failures of existing apparatus or inadequacy to give service, the theoretical research does not become of pressing importance. On the other hand, as soon as the operator experiences trouble, immediately the research becomes extremely vital. Hence, our experience with the study of dielectric losses in cables illustrates the great importance of the necessity of cooperation between users and manufacturers. The manufacturer must carefully study the experience of the operator and, on the other hand, the operating engineer must closely analyze his troubles and give the manufacturer the benefit of such experience.

H. W. Fisher: The writer will confine most of his remarks to Mr. Roper's criticism of American manufacturers and praise of foreign ones. Through correspondence from abroad, the writer knows that most of the so-called very high-voltage cables, concerning which much has been written in the technical press, have been operating, if at all, at much less than the designated voltage. Europe has apparently many engineers who try to keep their names before the public by advertising when they can, unusual work which is contemplated or supposed to be done abroad. When for any reason installation or actual operation at the stated voltage is delayed, a false impression is given, not only to the foreign, but also to the American public, of the actual accomplishment of foreign cable manufacturers and operators.

The writer has had access to actual tests of dielectric loss made in some of the cables abroad, and intended to be used at 33,000 volts, and the dielectric loss was so high that he can state with confidence that Mr. Roper would not operate the cables on his 33,000-volt system.

To be more explicit, I will state that the dielectric loss of this cable was over twice that required by Mr. Roper for his 33,000-volt cables. The cable was very well constructed and the physical properties of the compound were excellent, making very remote the possibility of transfer of the compound from one part of the cable to another. The manufacturer of this cable is a large concern with an excellent reputation and from the above information, it would seem that they are willing to sacrifice to a certain extent, dielectric loss in order not to neglect the other important considerations of cable construction.

R. W. Atkinson: The great questions brought to my mind by the subject of this meeting are "*What are the limits of the operating voltage of the cable, imposed by the voltage stresses in it, aside from the secondary effect of heating produced by dielectric losses*"? and "*What is the proper relation of insulation thickness to working voltage and what is the effect on the required insulation of the fact that the stresses are not uniform but are greater at the conductor surface?*" I will formulate some statements which I believe will be found fairly close to the correct answer to these questions. These questions will be discussed primarily from the standpoint of long continued stresses, though the answers apply in some measure to stresses applied for shorter time.

In his discussion, Mr. Peek has outlined an answer to these questions which is substantially the same as that which I have prepared but I believe that the matter is of such importance as to well bear a repetition, especially as my discussion is from a somewhat different viewpoint.

A theory departing very much from previous ideas has been advocated by Fernie and has recently been given much publicity in this country. This theory has been effectively refuted in the paper presented this morning by Mr. Simons which leaves the way clear for the discussion to be made without further reference to it.

I will now consider the questions with which I have begun this discussion. Taking up the second question first, I believe the law for such dielectrics as are in the cables follows very closely that which has been developed by Whitehead, Peek and Ryan for air. That is breakdown will occur not when a certain average stress is reached nor yet when a certain maximum stress is attained but will occur when this maximum stress is imposed on a certain definite amount of the dielectric. The reason in the two cases is very similar. In the solid dielectric a condition of failure must be the liberation of a sufficient quantity of energy to cause disintegration of the dielectric at the point of failure. This disintegration may be mechanical, or due to heat, or to direct chemical changes and the electrical failure is likely to follow rather than precede these other changes.

As a direct result of this a cable with a large conductor though standing a higher total voltage will withstand a lower stress next the conductor surface than one with a small conductor, and the same thickness of insulation, but the difference is much less than would be calculated on the basis of maximum stress and indeed may be unimportant for fairly large changes of conductor size.

The answer to the other question follows directly. That is the dielectric strength will be substantially proportional to the thickness for the same ratio of maximum to average stress. The strength will not increase quite in proportion to the thickness because this distance through which the stress must exceed the critical value is of greater relative importance in thin insulation than in thick. By way of illustrating the magnitude of this effect, it may be cited that experiments with insulation 100 mils thick that have shown dielectric strength say eight times what might have been expected from ten mils, 1/10 as much, of the same material.

There is not time even to begin to outline reasons and data supporting this theory. I will give some cautions to prevent misapplication. One of the most common reasons that low values of average dielectric strength are found for thick masses of dielectric in proportion to those found for thin layers is the heating due to dielectric losses. In other cases there is a great concentration of stress with the thick mass due to the shape of the electrodes. Where means are not taken to prevent discharges over surfaces, the electrical oscillations produced thereby are likely to be proportionately higher for the higher voltage and for the thick insulation. In many cases the thick insulation though supposedly of the same quality, actually is of lower quality than the thin insulation. Thus, there are many ways in which tests will be relatively very unfair, to the thick insulation in spite of the fact that say the same precautions were taken in all cases. That is, on account of the greater difficulties introduced by the higher voltage many precautions must be taken that need not be taken for the lower voltage.

It must be borne in mind that there is essentially a large difference between tests made where the voltage is rapidly built up to the breakdown point than where voltage is applied for very long periods as in service or say in accelerated aging tests. It is believed that the same fundamental considerations will apply in both cases but that numerical values may be enough different to cause a very important difference in the ratios of strength for short time application and long time application for specimens of different thicknesses of insulation.

Where a cable has composite dielectric, it follows that the limiting voltage is reached when the critical stress is reached in a sufficient portion of either of the two dielectrics. This may be in the one having the greater stress. That is usually next the conductor—or it may be in the other if the ratio of the dielectric strength is greater than the ratio of the stresses. Incidentally, it may be pointed out that all multi-conductor cables having insulation on the individual conductors and a belt or jacket overall, are essentially of the class of composite insulated cables inasmuch as the filler materials constitute an essential part of the insulation and may be the source of voltage limitation on account of their low dielectric strength, in spite of the lower stress there than in the main body of the insulation.

In 1920 Mr. Roper gave a paper showing the results of experience on the Commonwealth Edison system with lightning arresters. In a way his overhead system became an enormous laboratory and the results of these observations were epoch-making and, we understand, have revolutionized our whole ideas on the protection of distribution circuits and the development of new and far better types of arresters and even in the means used for testing and judging the worth of an arrester. He has now begun work with another part of his huge laboratory, this time with his underground system.

Mr. Roper is trying in this vast laboratory of his whether American cables can successfully meet conditions which have never before been met when we consider both the thickness of insulation for the working voltage and the service conditions. Speaking first of cables for operation at 25 kv. and less, vast quantities of American cables with thicker insulation have met successfully these conditions and there is a good deal of experience in Europe under their more favorable conditions with insulation thicknesses less than are common in American practise. But we know of no operating experience anywhere with these thin insulations combined with American operating conditions.

It is important to remember that, though laboratory and factory tests on this cable give reasonable assurance of successful operation, yet there is a very fundamental difference between such tests and the actual practical proof by large scale commercial operation. Laboratory tests have a very great value, in fact are the foundation of development, yet very misleading conclusions may be drawn from these when they are not backed by proper large scale experience.

Separate mention may be made of three-conductor cable for operating at 33 kv. More than one lot of cable in England is understood to have been placed in operation at 33 kv. during the present calendar year. These cables are understood to have an insulation thickness of one-half inch between conductors and the same amount between the three conductors and the sheath. All of these cables have round conductors. One English cable with thicker insulation and also an American cable have been in operation at this voltage for a greater length of time but the present interest centers in these newer cables. It is of interest to compare these with the American cables which Mr. Roper has installed during the last year for the same voltage. His cable with a 350,000 cir. mils sector conductor and 19/64 in. plus 7/64 in. insulation and 9/64 in. lead has a diameter of slightly less than 3 in. With sector conductor and the same insulation as used in this frequently quoted English practise, the diameter would be about 3.04 in., or with round conductors it would be 3.32 in. or about 12 per cent greater than that of the American cables. Thus though the British have used relatively thin insulation between conductors, they have been so conservative by use of thick belt insulation and unwillingness to use sector conductors that these much talked of cables are materially larger than the American cables and have more insulation as a whole. The comparison in favor of the American cable is still further emphasized by the statement that with round conductor and the insulation thickness used in English practise a 3-in. diameter cable could not have a conductor as large as 250,000 cm. instead of 350,000.

However, aside from the fact that European practise regarding insulation thicknesses is not so different from American practise as appears on the surface, or is sometimes mistakenly supposed or taken for granted, there is plenty of difference between European and American conditions to make comparisons very difficult. In two most important ways do the English make very sure that their cables are installed and operated so that they remain in exactly the original condition. In the first place, they take precautions about handling and bending the cable during installation that we understand are impractical under American conditions. Their cables are normally armored and it would be very difficult indeed to subject them to a serious amount of bending even if one wished to do so. It is true that English specifications are more severe in some particulars regarding bending test than is the American N. E. L. A. specification, though the English specification does not call for a low temperature at which the test is to be made, but we are not here concerned with the bending test which may be imposed under specifications. We are concerned with the actual installation conditions and with the fact that they are exceedingly careful to treat their cable with very tender care during installation and do not subject it to the degree of bending to which American cables are subjected. Thus the cable is installed in such a way that it remains in practically identically the condition in which it was originally made, and then it is operated with a maximum temperature of 55 deg. cent., or thereabout. This temperature limit is certainly not limited by dielectric losses unless these are far greater than is common in American practise. Under the favorable cooling conditions of installation directly in the ground, only very high dielectric losses indeed could cause limitations to this operating temperature. It is true that they are able to carry very heavy loads without exceeding this temperature but this limitation is quite surely because it is felt that the cables may deteriorate if heated to higher temperatures. This limitation may be nothing more than for instance the migration of the saturating compound due to fluidity at high temperature. If stresses are low we need not be concerned about that, but it is another matter if stresses are as high as allowable for cable in the original condition. We may very safely say then that whatever thickness of insulation is found satisfactory for conditions now obtaining commonly in American practise, a materially lower thickness will be equally satisfactory under conditions prevailing in England and other European countries, or conversely if our American operators can with like results use as thin insulation as can the Europeans, it means that they are getting better cables.

I believe that full study of the data will show that the American manufacturer has no cause to fear comparison of his recommendations or his product with those of European manufacturers. And let us give full credit to this operating company which is making this great experiment with its transmission system. Successful operation will be of material value to the operating companies of this country and to the industry in general. But let us conservatively remember that it is still an experiment, and let us not be too early in considering it out of the experimental field. And if this is concluded as a successful experiment let us remember the conditions under which it was made and not apply the results under still more severe conditions.

V. Karapetoff: This meeting represents a notable milestone in the development of cables and dielectrics. As an outsider, I note some tendencies which from my point of view seem desirable, and also a few remains of older undesirable tendencies in the methods of attack.

Perhaps the most desirable tendency is a steady, cooperative work, as contrasted with former sporadic individual efforts; also due respect to the work of preceding investigators, and a most excellent bibliography. This attitude alone vouches for the success of the enterprise.

Another desirable tendency is a change from looking upon a cable as a unit piece of apparatus, to a careful analytical study of its elements. I was once crossing the frontier between two European countries and had with me two presents, a fine silk shawl and a very heavy metal box. The customs inspector put them together on a scale, found the total weight, multiplied it by a coefficient, and told me what duty I had to pay. Many of the older experiments on high-tension apparatus remind me of that summary proceeding. A piece of cable is "shot," a result is obtained, and presented to the public for future digestion. The tendency in the present papers is distinctly away from that pernicious practise. The dielectric is separated into paper, petrolatum, moisture, and what not, and the properties of these materials are treated separately in a more or less scientific and rational manner.

Finally, I welcome most heartily the tendency to speak of the phenomena in dielectrics in terms of the recent ionic and electronic theory of electricity. I appeal to my fellow-teachers to see in this tendency an encouragement of our endeavor to present electricity to our students in terms of the ionic theory. In a few years our graduates will not be able to read Institute papers unless they become familiar with the electron theory.

As to undesirable tendencies one is exemplified by the Fernie theory. It reminds me of those old empirical rule-of-thumb formulas, and is a dangerous step backward. I was glad to hear a speaker oppose this theory.

The other tendency which I rather deplore is to extrapolate theoretical formulas derived from stresses within the elastic limit, and to apply them to the phenomena at the rupture of a piece of insulation. What would we think of a specialist in strength of materials who would use the results of the theory of elasticity in discussing the ultimate strength of a column or a beam? Could he legitimately use a theory which does not apply there? Take a continuous beam on three supports; as long as the stresses are within the elastic limit, the load can be increased and all of the stresses will be in proportion. But load the beam beyond the elastic limit, for example so that the middle support begins to yield, and you will get an entirely different distribution of stresses, unforeseen by the theory of elasticity.

This is apparently done in some of the papers presented today. The logarithmic formula which holds for dielectric stresses within the elastic limit, is being applied to the discussion of stresses which lead to the failure of a cable. I hope that this inaccurate way of reasoning will be gradually eliminated from our papers.

I would suggest to the Committee the necessity of extending our terminology in this branch of electrical engineering. Whenever there is progress in the art, we must not be afraid to introduce new terms. I notice that Mr. Del Mar used in his introductory remarks the expression "imperfection angle." This I think is a legitimate and useful term for characterizing a given cable. A cable has an imperfection angle of 5 deg., against some other cable with an imperfection angle of 9 deg. etc. We also need a new term to distinguish cables in which the ratio of radii is below 2.72 and above 2.72. It is rather awkward always to mention this ratio. Let us call one of them type *A*, the other type *B*, or thin and thick insulation, or something else, but let us not be afraid to introduce new names for these two types of cables.

B. Welbourn: Perhaps the best answer I can give to Mr Fisher is to state one or two facts which are within my own knowledge as one of the engineers connected with cable work who has been right through the development from the early days of high-voltage cables in our country. We have a considerable quantity of 33,000-volt cable at work. In one installation, on which I have all the information, a large number of tests have established that the dielectric loss per mile at 50 cycles, with a conductor working temperature of 140 deg. fahr., 60 deg. cent., is exactly 2 kilowatt-hours. I think that you state your losses in terms of watts per foot, and unless my arithmetic is wrong, that is 0.38 watts per foot. I may say that considerably better results have been obtained since.

A cable manufactured by my company has been at work in England for the last two and one-half years, working with a stress of 5,530 volts per mm., as calculated by the Atkinson formula. There are 3-core cables in service working with 4400 volts per mm. I think you call it 44,000 volts per cm. in your phraseology. I can state definitely that 44,000-volt three-core cables are commercially possible.

A great advance has been made in our country with regard to the question of dielectric losses. Forty-four thousand-volt 3-core cables can be supplied which will have a power factor not exceeding 1 per cent, up to a working temperature of 130 or 140 deg. fahr.

A good deal of attention has been given today to Mr. Fernie's minimum stress theory. He is a friend and, until two years ago, was a colleague of mine. He developed his theory about 1914, and the results which he has published in the *Beama Journal* are based on experimental work done at least seven years ago.

At the time Mr. Fernie reached his conclusions, he caused a great deal of discussion in my company, as you may imagine and I might say that his results have never been accepted by my company. I think that much later work which has taken place since Mr. Fernie left the company, and went out of the cable business has shown that his theory has to be provisionally laid aside until a completely new lot of data can be accumulated on cables of the latest manufacture.

I would therefore suggest to Mr. Simons and the other gentlemen who have been discussing Mr. Fernie's theory that they lay it aside for a time, until they have done further experimental work on up-to-date cables.

I have been rather surprised in looking over your literature on cables, to see how little attention has been paid to the subject of the thermal resistivity of the insulation. It is the same in our country, but to the operating companies, and to the engineers who have to prepare the specifications for cables, I would strongly suggest that they call for very stringent guarantees on the thermal resistivity of the cables they are buying, whether they be for high or low-voltage work.

D. M. Simons: In considering Fernie's data, I mentioned that it was unfortunate that his tests did not include a greater range of the ratio R/r, or D/d. The paper by Messrs. Middleton, Dawes and Davis contains a valuable contribution in this respect, since their breakdown tests cover four times as great a range of D/d as Fernie's. It is interesting to see that their tests show that the minimum stress is by no means constant.

The authors have apparently concluded from the data of their Tables 1 and 2, that the maximum stress at breakdown is a constant for cables in which D/d is equal to or less than 2.72. This does not seem to be justified as a definite conclusion since there are appreciable variations in their test values, and in fact, the variations are about half as great as those of their average stresses.

I feel that the comparison of the maximum stresses in three-conductor cables as calculated by the so-called old and new methods is open to considerable criticism. In the first place, they assume in this comparison that the maximum stress at breakdown is a constant, and the same for single-conductor and three-conductor cables. Secondly, the so-called old formula for a stress in three-conductor cables gives obviously a stress considerably too high. The actual cable consists in one leg of two parallel cylinders with the delta voltage between them, and for this condition the old method substitutes one cylinder of the correct diameter, surrounded by a large concentric cylinder, with the same insulation thickness and the same voltage. It is well known that the maximum stress in the former case is always considerably less than the latter. The accuracy of the new method has been so thoroughly substantiated that the tests shown by these authors do not tend at all to disprove this method, but rather to show that the maximum stresses occurring at breakdown in the three-conductor cables tested by them were much lower than the maximum stresses in the single-conductor cables tested.

Mr. Welbourn has apparently obtained a meaning certainly not intended by Mr. Fisher's remarks. Mr. Fisher by no means intends to imply that none of the high-voltage cables mentioned in the foreign press were in operation, since we have every reason to believe that certain ones are under full rated voltage.

On the other hand, he has attempted to point out that it seems quite sure that many of the described installations are not in operation. I might mention specifically the cut which appeared about a year ago in the *Electrician* showing a large three-core cable "for 66,000 volts." Our information seems quite definite that this cable is not in actual operation, but is merely a short experimental length.

Mr. Welbourn has apparently replied to Mr. Fisher's remark about the dielectric loss in a foreign cable by mentioning the very low dielectric losses in British cables, I am sure that Mr. Fisher's comment was by no means meant as a criticism, but quite the contrary, and that he merely desired to show that certain foreign manufacturers at least did not consider it necessary or advisable to go to extremely low dielectric losses.

J. B. Whitehead: In discussing the potential gradient at the surface of the central conductor of the cable it is perhaps worth while to recall that the value which we use is based on the elementary laws of electrostatics acting in a perfectly continuous medium, such as the ether.

We should remember that when we introduce a dielectric we may through the polarization modify the forces existing before its introduction. For we know that even a perfect dielectric is made up of discreet molecules and that under electric stress the component charges of these molecules are drawn apart. Remembering also the space separation between molecules themselves, it is not difficult to picture such a space arrangement of charges, around a circular conductor as would alter the value of the electric intensity pertaining to a continuous medium. For example we may imagine the dielectric in a single-conductor cable as arranged in concentric layers of molecular thickness, and the component charges separated radially under the electric field. In each layer the inside charge would be nearer the central conductor, and owing to the space separation, would tend to lower the normal value of the intensity in the next inner layer. The amount of this lowering would depend on the radial and circumferential space separation of the charges, but reasoning in this way, it is not difficult to picture the stress in the layer next the central conductor as being reduced to a value comparable with or equal to that in the layer next the sheath. This would account for the evidence that cable breakdowns do not always begin at the center, and would permit us to think that a perfect dielectric at least may have a definite dielectric strength. There is good reason to believe that the gradient necessary to ionize a molecule has a definite value. But air and oil and perhaps other dielectrics always do begin rupture at the center as in the corona. Does not this upset the foregoing suggestion? Not necessarily, for neither air nor oil is the perfect dielectric we have pictured. In each of them, in air particularly, free ions, that is, independent charges, are always present in a certain quantity. These charges, unlike the neutral molecules may move freely in the electric field and so may cause a still further modification of the gradient at the center. It is in some such phenomena as these that the explanation of the peculiar law of corona will ultimately be found. It is probable that we shall never attain the perfect dielectric, but it would appear that the stiffer cable compounds would offer less freedom of movements to independent ions, and so would be less liable to departure from the ideal structure in this respect.

Here, however, new troubles await us, for we encounter conducting filaments, moisture particles, and other departures from homogeneity, any one of which may cause a further modification of our fundamental expression for potential gradient. Consequently, it is of great importance as already pointed out by Professor Karapetoff, that in analyzing the problems presented in cable construction, every care be exercised to separate all the elements entering. The occurrence of corona, or more properly, ionization, in thin air layers, has been recognized for some time. Suspected only at first, its presence was next indirectly shown in the break in the dielectric loss curves of cables, and subsequently its presence has been made visually manifest in air layers between glass plates. Mr. Shraders' power factor curves on one sheet of insulation and an adjacent film accentuate sharply the influence of this state of ionization. It is important to note, however, that his curves are all plotted with the average potential gradient as abscissas, and consequently they do not express the behavior of the air alone, but only the combined behavior of insulation and air. It is for this reason that the rise in the power factor curves is gradual for the thinner air films, and steeper for films of increasing thickness. Ionization begins at a definite value of potential gradient, and consequently the power factor curves plotted against gradient in the film, would all of them show a sharp ascent at the critical gradient.

The sharp maximum of power factor indicates that above the critical gradient the normal charging current increases more rapidly than the ionization loss, and suggests that the principal loss is due to the process of ionization, rather than to a resulting resistance of the air film.

W. C. Hayman: Mr. Roper, in his paper, has given us some very good data on dielectric losses and stresses on paper insulated cables. His conclusion, however, that in low-loss cables the temperature is limited as in low-voltage cables by the temperature which the insulation will stand without deterioration, does not agree with results we have obtained from a number of tests. We have found that the breakdown voltage of low-loss cables decreases with increase of temperature. The average breakdown voltage will decrease between 25 deg. and 100 deg. cent. as much as 25 per cent.

We should also make a study of the effect of high temperatures on compounds used for impregnating high-tension, low-dielectric loss paper-insulated cables, before we make any change in the present standard temperature ratings.

Referring to Mr. Simons' paper regarding Fernie's theory, it would seem that more experimental data are necessary before we discard some of the older theories regarding stresses in the insulation. We have found from tests that breakdown voltage on small conductors is less than on large conductors where the insulation thickness is the same. As the breakdown varies so widely, however, on samples cut from the same cable, it is necessary to make a large number of tests.

William H. Cole: In cable specifications with which I am familiar, dielectric losses are specified to be relatively low, but no other essential quality is to be unduly sacrificed on that account. I believe certain manufacturers have been neglecting some of these other qualifications of good cables. In one case at least, while continued reduction in dielectric losses has been effected, the saturation of the paper dielectric has become less perfect. I do not refer to longitudinal migration of compound with which many engineers are familiar, but to continual radial absorption by the paper of compound from the filler spaces. Such cables are apparently well saturated when they are delivered and remain so while held in storage. After being in operation from one to two and one half years, some of these cables develop serious voids in the filler spaces, so that we are now meeting with trouble due to ionization in the central part of the cable.

Tests have been made which indicate that ionization has an oxidizing effect on the compound. Stethoscope tests show that the used cables have a larger percentage of voids, than unused sections from the same original lot.

On the whole it appears to be a question whether or not the manufacturer in arriving at low dielectric losses has acquired sufficient knowledge of the characteristics of his impregnating compound, how much compound he puts into his paper, how much he leaves in the filler spaces, and how long that compound will remain in the filler spaces. The importance of this subject was realized years ago—that compounds must not only be introduced into the cable to a sufficient extent to fill all voids, but that there shall be no chemical or other action within the cable after the cable is placed in service.

On the subject of d-c. testing of cables the class of cable referred to failed recently under a d-c. routine test. The faulty section was carefully examined disclosing the radial absorption effect, the ionization of the voids and the oxidation of the compound. The cable under test had been in continual service, was supposed to be in a sound condition, and the operating pressure between conductors had been of the order of 24,000 volts. The d-c. test voltage was 40,000 volts or less than two times the a-c. operating pressure. On the basis of the factor of 2.4 the cable failed at a voltage much less than the d-c. equivalent to the a-c. operating pressure. The condition of the dielectric at the point of failure seemed to show conclusively that so called, "spitting" and re-healing of the dielectric had been taking place for some time under a-c. operation. The only conclusion to be drawn is that d-c. voltage is probably more effective in breaking down incipient faults than a-c. voltages and that the ratio of 2.4 between d-c. and a-c. holds good only for dielectrics in perfect condition.

It may be of some slight interest to know that tests on high dielectric loss cables have been made for the purpose of determining whether or not the potential gradient is very much altered by temperature gradients, and while it is of no particular interest today, since no one uses high loss cables willingly, it has been found possible, with sufficient fall of temperature between the copper and lead, to change the distribution of the potential, so that the outer layers receive very much higher stresses than would be calculated for uniform temperature. This may be a possible explanation why some of the old type high loss cables could become so badly charred before final breakdown.

G. B. Shanklin: Mr. Roper's study of current carrying capacity and critical temperature is based on an average duct radiation curve taken from a paper by W. S. Clark and myself read before the Institute in 1919. Available data on duct radiation constants are very meager and our curve was given merely as an illustration with no intention of introducing it as a standard. Since then a few additional data are available and a closer study of our original radiation curve indicates it to represent about 25 per cent better thermal conditions than actually exist in the average duct. Our original "hot spot" radiation curve more nearly represents the true average curve than our original average curve does.

It was with some misgivings, therefore, that I noted Mr. Roper had based his calculations on the average curve and it is surprising to find how well his practical observations and experiences check his calculations. I believe this is accounted for, at least, in part, by the fact that his dielectric loss values assume a uniform temperature through the cable cross section, equivalent to the copper temperature whereas, in actual practise the temperature is graded through the cable cross section, giving a lower dielectric loss than he assumed.

A standard average duct radiation curve would prove useful and if one is ever adopted it would be much better to represent the temperature drop from sheath to ambient soil. The curve would then be independent of the type of cable placed in the duct, except insofar as influenced by sheath diameter, which under ordinary conditions is a factor of no more importance than several others that are ignored in this "short-cut," approximate method.

Mr. Roper's statements regarding the variation of dielectric loss over lengths of cable might lead to misinterpretation. I believe he referred only to high loss cable of the rosin-oil-filled type. The better grades of low loss modern cable do not show such wide variations with length.

An interesting feature brought out by Mr. Roper's study of critical temperature is that, although the Institute temperature rule of 85 deg. cent. applies very well for the old type, high loss cable it is too conservative for the new type, low loss cable.

I have only one conditional exception to take with Mr. Roper's conclusions. He shows quite clearly that the quality of cable insulation has been improved to a point whereby there is little danger of cumulative heating under normal operating conditions. He also shows that this new type of cable meets the standard high-potential test with ease. On the strength of this advancement he recommends that insulation thickness be reduced. There is no doubt but that the thickness used in this country can be safely reduced, but I feel that Mr. Roper has overlooked one important factor, and that is internal ionization.

The state of the art has progressed to a point, now, where internal ionization will be the limiting feature in any further reduction or gain. It is to be regretted that more is not known about this feature. We know that when voids or gas spaces are present in a cable that ionization occurs when a certain value of stress is reached. The conditions under which this ionization is likely to occur in service, its nature, whether it continues indefinitely and the amount of damage it can do is not clearly understood. We are at present making a study of these factors and hope to throw some light on them in the near future.

Ionization cannot be ignored. No matter how compactly made a new cable may be and how tightly the sheath is applied, voids form in service. Expansion and contraction loosens the lead sheath, causing it to "crawl" to a more or less extent, thus forming voids. Under laboratory test conditions these voids just under the sheath are ionized at a stress on the insulation (minimum stress) of about 14.0 kv./cm. What occurs in actual operation when the minimum stress exceeds 14.0 kv./cm. we do not know yet. Our work thus far indicates that ionization usually starts first, next to the sheath and not next to the conductor as previously assumed, although we are not prepared to state this conclusively.

Mr. Simons' paper on the dielectric strength of cables is too theoretical and speculative to be of practical application. Papers of this type are interesting and help us form a better mental picture of what might happen in a cable at breakdown. What actually happens is another story and probably involves too many factors to be so simply explained.

The mechanics of breakdown in gases is now fairly well understood and the parallel problem of liquids is well on the road towards solution. Gases are homogeneous and readily applicable to theoretical study. It is but natural that they should first give up their secrets. Liquid insulations are not so homogeneous but far more so than solid insulations. Investigators began to make real progress with the mechanics of breakdown in liquids only after the factors introduced by foreign impurities, such as moisture, dust, etc., were recognized and eliminated.

The same principles will have to be applied to a study of the mechanics of breakdown in solids. One of the greatest difficulties is in obtaining even an approach to homogeneity in solids. We must first learn something about the theory of breakdown with simple homogeneous solids in a parallel field and explain why the breakdown stress usually depends upon the thickness of insulation. Later we can go to more complicated built up commercial insulations in parallel fields and finally to cables, in which the non-parallel dielectric field adds further complications. What is needed at present are more actual breakdown data on cables, such as published by Fernie, and the very interesting data presented at this meeting by Messrs. Middleton, Dawes and Davis.

The paper by Del Mar and Hanson impressed on two counts, as we have done work along similar lines. Their theoretical study of dielectric loss is clearly and remarkably put forth and agrees with measured results better than any of the several theories that have been advanced at various times.

Several years ago we found by trial that the equivalent dielectric circuit could be closely represented by an arbitrary circuit similar to their Fig. 2. The component which they designate in their formula as "resistivity of cellulose fibers," however, should be called, "unknown factor," for it must surely represent more than the resistivity of the cellulose fibers. (It probably represents also the moisture resistivity.) The effect on dielectric loss of this component is small. I fully agree with their statement that dielectric loss is largely determined by the resistivity of the impregnating compound, for we have made numerous measurements that verify this in every particular and have found much the same relation between power factor and compound resistivity as given in their Fig. 3.

In one other respect, our work verifies theirs. The conductivity of compound alone, and hence, the power factor and dielectric loss of finished cable, gives every appearance of being mostly due to ionic conduction. It may not be true ionic conduction of the electrolytic type but it is some sort of uniform migration or transfer of charged particles such as metallic conduction. One of the best proofs of this is the almost exact agreement between d-c. and 60-cycles a-c. resistivity of compounds at temperatures above their melting points. Divergence occurs only at lower temperatures where the compound is in solid form. There is a sharp upward break in the resistivity curves when the solidifying temperature is reached.

The conclusions arrived at by Messrs. Del Mar and Hanson concerning dielectric strength are not so convincing. They attempt to explain the dielectric breakdown by this same theory of ionic conduction. If they are referring to slow breakdowns of the accumulative heating type their theory holds quite well, such failures should be called conduction breakdowns, but the term dielectric strength is recognized as applying only to those breakdowns that occur soon after the test voltage is applied and before accumulative heating takes command.

Under these conditions there is no relation between dielectric loss and dielectric strength of cables. Quite often cables having the lowest dielectric loss also have the lowest dielectric strength and vice versa. Still more convincing proof that the conduction and dielectric strength are unrelated is furnished by tests on the compound alone. Here, there are no cellulose fiber barriers, the charged particles have a free path between electrodes. One would naturally expect the relationship to be brought out more distinctly than in cables. The results, however, are even more divergent than in cables. Compounds having low resistivity often have high dielectric strength. If moisture or dust is added to a compound of high resistivity its dielectric strength can be reduced to a negligible value without effecting its resistivity at all. The resistivity of any compound varies enormously with temperature while its dielectric strength is effected hardly at all by temperature. This same temperature characteristic holds, approximately, for solid insulations.

I have studied dielectric strength for a long time, and have never found a theory that applied better than the old analogous theory of mechanical impact stresses and strains.

There appears to be a tearing apart of the molecular structure similar to mechanical rupture. Some materials are electrically brittle and some electrically elastic, analogous to mechanical brittleness and elasticity.

One of the most vital factors appears to be concentration of stress, set up by local high frequency. As an illustration, a poorly filled cable can be considered. Every one knows that a poorly filled cable has relatively low dielectric strength. This is due to concentration of stress, set up by local high frequency. When the applied voltage reaches a certain value, the voids in the cable cross section are ionized. At first it is merely a faint glow but as the voltage increases there is an increase in intensity of discharge and appearance of local high-frequency oscillation. The localized stress thus caused tends to start rupture and final breakdown. This might first start at the conductor, at the sheath or wherever the voids happen to be located.

Mr. DuBois, in his present paper advances a theory of dielectric loss somewhat at variance with that of Del Mar's and Hanson's. He attempts to account for dielectric loss as due to a certain peculiar behavior of moisture content. I believe if both theories were combined in their proper proportions a very good working theory would be produced. The whole trouble seems to be that Del Mar and Hanson ignored moisture while Du Bois over-emphasized it. It is only in cable not thoroughly vacuum dried that the moisture component of dielectric loss is comparable with that component produced by the conductivity of the impregnating compound. I am certainly inclined to agree with Del Mar and Hanson in their conclusion that the last named component predominates in modern, low loss cable. All of our experience points in that direction.

Messrs. Middleton, Davis and Dawes deserve a unanimous vote of thanks for their splendid paper and the admirable way in which they have handled dielectric strength, a subject involving many, as yet, unknown factors. Their empirical results are original and impressive. It will be interesting to see how well they stand the test of time and additional trials.

If Mr. Middleton had looked up a paper on cables presented before the Institute in 1917 by W. S. Clark and myself he would have found evidence supporting his conclusion that automatic grading due to voltage stress and temperature distribution is of negligible amount.

Mr. Shrader's paper on "Corona in Air Spaces in a Dielectric" does not leave much room for doubt concerning the cause of the peculiar and abrupt change in dielectric loss that occurs in practically all commercial forms of solid dielectrics when the voltage is increased. It is, as we have always contended, due to ionization of the entrapped gas. It is to be regretted that Mr. Shrader did not include data on permittivity, temperature, etc., which would have enabled those engineers who have worked along similar lines to make a better comparison between his work and theirs. His method of presenting results is, in every other way, exceptionally good, but I do not agree with his conclusions that these results cannot be theoretically applied.

J. L. R. Hayden: In our investigation on insulated materials during the last few years we made the same observations, which are in good agreement with Mr. DuBois explanations on the effect of moisture in insulating materials. We have been able to reproduce experimentally some of the phenomena discussed in the paper in such a manner that they can be visually observed. For instance, the action of moisture particles in forming threads and bridging between terminals, is illustrated in Fig. 1 of the paper. This can be shown conveniently in the following manner. As insulating materials we use a light colored viscous oil; as terminals two spheres of 2.5 cm. diameter and 1 cm. distant, and impress about 10,000 volts between the spheres, that is, much less than the voltage which the oil gap would stand, Then a small amount of moisture is dropped on the oil by a dropper, in small drops. These drops can be observed to drop slowly through the oil, until they approach the electrostatic field. Then they are rapidly sucked into the field, and each drop elongated into a thread, and the thread lengthens, until it bridges between the electrodes. Then a flashover and the thread is destroyed by turning into steam by the heating effect of the current through it. In this manner flashes occur for a considerable time in intervals of a few seconds by drops entering the gap, lengthening into threads and bridging the gap.

Very interesting and suggestive also are the motions of the drops, which depend on their position in the electrostatic field, and on the nature of the field, whether unidirectional or alternating.

N. L. Morgan: Mr. Simons has mentioned several theories which attempt to account for the breakdown of single-conductor cables having the radio R/r greater than 2.72 and he has also suggested another theory to explain the results obtained by Fernie. After reading his paper, I do not feel entirely satisfied with his explanation. I think that it is an advance over the other theories that have been suggested but do not think that it has been carried far enough.

I do not see how insulation can be overstressed and at the same time not destroyed. Several investigators have shown that so-called "overstressed insulation" is really due to temperature rise, and the effect eliminated after a period of rest. It seems to me that the breakdown of single-conductor cables, having the ratio R/r greater than 2.72, is due to change of dielectric constant of the portion of the insulation near the conductor. As a voltage is applied to the cable, the stress in the portion of the insulation near the conductor increases and consequently the increasing dielectric loss causes the temperature to rise. Although the a-c. dielectric constant does not change below 50 deg. cent. it does vary considerably above 100 deg. cent. If, therefore, the inner portion of the insulation is several degrees hotter than the portion near the lead, we may have the equivalent of a cable with graded insulation and the cable would withstand higher voltages than would be expected.

This also explains Fernie's statement that small conductor cables withstand higher maximum stress than large conductor cables with the same insulation wall.

From the above one might think that the greater the dielectric loss of a cable is, the hotter it will get and therefore the greater will be the breakdown voltage of the cable. But as mentioned above, breakdown is really a charring of the dielectric, that is, a strictly physical phenomenon, and the cable with the greater dielectric loss will reach this charring temperature first.

When voltage is applied suddenly, the heat generated near the conductor where the stress is greatest has not sufficient time to be conducted away and the grading effect will be much more marked than if the voltage is increased slowly and the heat given time to be conducted to the sheath. That is, a cable will withstand a higher voltage when it is applied quickly than when the cable is subjected to long period test, which has been found to be the case in practise.

It seems to me that a satisfactory theory of dielectric breakdown, will not be arrived at until we take all the factors into consideration. The theory cannot be based on only one class of observations, but must be based on the temperature of the dielectric, its dielectric loss and constant, its insulation resistance, its specific heat, the thermal conductivity, its shape, its dimensions, and the inter-relation of these different properties. When all these things have been taken into account, then we will be in a position to formulate a theory of dielectric breakdown.

C. P. Steinmetz: An extensive investigation of this problem of the mechanism of the breakdown of solid insulation, has been carried out during the last few years in my laboratory by Mr. Hayden and his assistants, in which we derived the conclusion, or rather, are forced more and more to the conclusion that there exists no such thing as a definite breakdown voltage or breakdown gradient of solid insulation.

It seems to look more and more as if the electrical breakdown of solid insulation under electrical over-stress is not analogous to the mechanical breakdown of a structure under mechanical overstress, but is a phenomenon of an essentially different nature, and different character, and is related to the electrical characteristics of the third class conductors. I have discussed this type of conductor on a number of occasions, the so-called pyro-electric conductor. It is a type of conductor little studied. It is characterized by a volt-ampere characteristic in which over a certain range of current, the voltage decreases with increasing current; so that in such a conductor, if we impress a voltage and gradually increase it, the current passing through the conductor first increases proportionately to the voltage, then begins to increase more than proportionately to the voltage, and finally, the resistance decreases with increase of current at such a rate that the voltage does not further increase, but the current continues to increase. A further increase of current results in a decrease of the terminal voltage across the conductor, and with increase of current, the voltage decreases to a minimum. Beyond this the voltage may again increase slightly. That is, in such a conductor there is a maximum voltage point at a certain intermediate current. The results of our investigation seem to show that what we call a solid insulator, is, at least in many cases, a third-class conductor—a conductor of a type in which the current at the maximum voltage point is extremely low.

Considering then the solid insulator as such a third class conductor. By impressing constant voltage on it, and gradually increasing the voltage, you will find that the current, passing through the insulator, increases, first proportional to the voltage, and then more than proportional, until the maximum voltage point is reached, and there the current runs away, rapidly, practically instantly rises, up to the short-circuit current of the voltage supply, which means the destruction of the conductor by heat and the elimination of all that can be seen. We have succeeded, by limiting the power, to carry these volt-ampere characteristics of the insulator beyond the maximum voltage point, and observe that part of the volt-ampere characteristic, where the increase of current means a decrease of voltage, where, as we would speak of insulators, the insulator is over-stressed. We find that at the maximum voltage point, which would be considered in general as the breakdown voltage, the disruptive strength of the insulator is not impaired, and we may go materially above this, and still have the insulator unimpaired, no change, no damage. It is the unlimited concentration of energy, resulting from this characteristic at constant voltage supply, which leads to the destruction which we call breakdown.

But, by limiting the energy, we have been able to go beyond the maximum voltage, and we have been able to study the behavior of solid insulation in this range.

From this it follows that in dielectric fields where the shape of the field is such as to limit the energy which can be concentrated in an overstressed portion of the dielectric, as is the case, for instance, with a cable with a high ratio of external to internal diameter,—with such a structure a part of the insulation can be stressed above the so-called breakdown point of the insulator without changing the insulation.

In this case the logarithmic law of voltage distribution does not apply any more.

You see all these are conclusions which have been brought out very nicely in a number of these papers. Furthermore, it follows that the rupturing voltage of a solid insulator, with continuous voltage and alternating voltage, are in a constant relation, and this relation depends on the nature of the insulator, and this seems to offer a possibility of the study of actual voltage distribution in the insulator, not merely at breakdown where the voltage distribution really means but little, but before and after the breakdown, and so get some idea of the mechanism of the breakdown.

It follows, for instance, that with regard to the overstressed portion of the insulator, the voltage gradient does not collapse, but remains finite, though lower than in the portion of the insulator which is not overstressed.

We may consider the maximum voltage point of the solid insulator as third-class conductor, as the breakdown point. However, this maximum voltage point of the volt-ampere characteristic is not a constant, but depends on very many conditions. It depends on the nature of the insulator, on the energy developed in the insulator, or near the insulator; on the heat conductivity and on the heat storage capacity of the insulator and of all surrounding material, and also on changes taking place in the insulator with temperature, etc. Mr. Roper's paper was interesting in showing a number of features that bring this out, although I have not had time yet to numerically check up these figures.

There is still a large amount of work which will have to be done, before we can really be perfectly certain of this conception of the solid insulator as a third-class conductor, by which the electrical volt-ampere characteristics determine the behavior of the insulator in the electrostatic field. There will still have to be much experimental work done, and the conclusions which we derived therefrom, verified; but it is to be hoped, at a meeting similar to this, it will be possible for Mr. Hayden to present a paper on the mechanism of breakdown of solid insulation.

G. A. Anderegg: In connection with the problem of dielectric loss in power cables it may, perhaps, be of interest to make a brief statement regarding similar losses in telephone cables at frequencies higher than those customarily considered in power circuits.

Telephone transmission ordinarily occurs at voltages far below the limiting strength of the insulation, and the entire power loss in such cables normally has no appreciable effect upon their temperature. In such cases the dielectric losses are of importance, therefor, not from the standpoint of heating or of breakdown strength but from the standpoint of attenuation, especially in case the cables are artificially loaded with inductance or are operated at the high frequencies used for "carrier" transmission, when the dielectric loss may add substantially to the total power loss and transmission loss. It is, therefore, important, especially in long loaded cables, to take special precautions to have the dielectric loss as low as possible.

It has long been recognized that the capacity and insulation resistance as measured with direct current by means of a galvanometer do not accurately represent these properties for a cable operated at frequencies of hundreds or thousands of cycles per second. Great numbers of measurements of capacity and dielectric loss of circuits in telephone cables have, therefore, been made by means of a specially designed bridge, briefly described by G. A. Campbell in the *Electrical World* and *Engineer*, April 2, 1904. It has been found convenient to express the results of dielectric loss measurement in the form of the conductance of the circuit; *i. e.*, the admittance of an actual circuit having capacity and dielectric loss is represented as if it consisted of a pure ideal capacity shunted by a conductance. To make a ready comparison of different circuits, it has been found convenient to consider for each the value of the "damping constant" $G/2C$, in which G is the conductance in micromhos and C the capacity in microfarads. This expression appears in one form of the attenuation constant for a loaded circuit, and when its magnitude is known for the desired frequencies it serves to indicate the quality of the insulation from the standpoint of dielectric loss.

With the types of insulation most commonly used in telephone cables it has been found that the conductance is approximately proportional to frequency throughout the ordinary range of telephone frequencies, though increasing somewhat more rapidly than proportional to frequency. It is independent of the applied voltage so long as this is kept well below the breakdown strength of the insulation, as is the case in normal telephone operation.

Since the conductance increases with frequency it follows that for a given effective voltage the dielectric loss is greater with a complex wave form than with a pure sine wave form, because the higher frequency components of the complex wave form act upon a higher conductance and, therefore, contribute a greater dielectric loss than they would if conductance were independent of frequency. This fact may have some bearing on the advantage of a good wave form for power transmission in cables.

In many telephone cables low capacity and low dielectric loss, rather than high breakdown strength, are controlling requirements. The design of such cables differs greatly from that of power cables, the commonest form of insulation being air and dry paper without impregnating material, only enough paper being used to give the spacing of wires needed to secure the desired capacity and the necessary firmness to make it possible to handle the cable successfully during installation. Such construction makes possible a very low dielectric loss. In some cases the power factor, or sine of the "imperfection angle" at 1000 cycles per second may be as small as 0.002, or sometimes even less.

Changes in design or treatment which tend to increase the insulation resistance for direct currents usually tend also to decrease the conductance for alternating currents and to decrease the excess of the capacity at low frequencies over that at high frequencies, though there are no definite relations between these quantities. In the ordinary ranges of working temperature the conductance of the usual types of telephone cables increases with increase in temperature, though in many cases there is a temperature of minimum conductance, below which a further decrease of temperature again results in increased conductance. Certain insulators, for example rubber compounds and gutta percha, in many cases show a very markedly higher conductance at temperatures approaching the freezing point of water than at more ordinary room temperatures, although their direct-current insulation resistance is much greater at the lower temperature.

W. D. A. Peaslee: With reference to the paper by Messrs. Middleton, Dawes and Davis, there are several very interesting points brought out that add materially to the large amount of data that has accumulated during the last few years leading to a serious question as to the validity of our past theories with regard to the mechanism of breakdown of a dielectric.

It would seem that it is time for a very serious consideration of our past theories in the light of the accumulated evidence of the last ten years of investigation in the field of the so-called dielectrics to see if there is not something fundamentally wrong with our ideas regarding these materials. For sometime I have been drawn very positively to the feeling that there is no such thing as a dielectric, that the substances we have ordinarily regarded as dielectrics are merely conductors of enormously high resistivities and furthermore the accumulating data secured by means of high-voltage direct current with considerable energy available, points to the conclusion that most of the so-called dielectrics are conductors wherein at some point of the volt-ampere characteristic the volt-ampere coefficient changes from positive to negative following more or less the curve shown in Fig. 1. Dr. Steinmetz' remarks at this meeting have strengthened very greatly the author's convictions in this matter. If we refer to Fig. 1 we note that for a certain increase of current the voltage across a given path of such an insulating material (so-called dielectric) increases in proportion to the increase in current density. At the point "*A*" on the curve this increase departs from a strict proportionality, the coefficient steadily decreasing until at *B* the coefficient has become *O* and an increase in current density does not entail an increase in voltage. Beyond the point *B* an increase in current density actually occurs with a decrease in voltage across the conducting path.

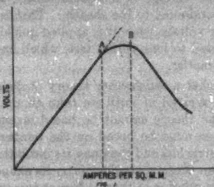

Fig. 1

We have, in the past, rather accepted the mechanism of dielectric breakdown as expressed in the old rule "whenever for a finite period of time the dielectric flux in a given dielectric exceeds a certain critical value for that material the dielectric is destroyed." I think that this theory is subject to very positive challenge in the light of present accumulated data. The acceptance of such a theory of breakdown has led to the discrepancies in interpretation of observed data, such as have been brought out in the paper by Fernie's "Minimum Stress Theory" and other theories discussed in these papers.

Let us for a moment examine what occurs in a cable as voltage is applied between the conductor and sheath. Admitting for a moment the hypothesis that the so-called dielectric is merely a conductor of the class described of extremely high resistivity, assume a conductor of radius r surrounded by an insulating material whose volt-ampere characteristic is given in Fig. 1 which is in turn surrounded by a lead sheath whose inner surface is at a radius R from the center of the conductor. We will designate as x the radius of any point under discussion at any time. As voltage is applied between the conductor and sheath, a very minute current will begin the flow through the insulating material. The current density naturally is greatest at the surface of the wire, decreasing, at a given applied voltage, as we approach the lead sheath. As the voltage is increased the current flowing through the insulating material increases in proportion to the applied voltage until at the surface of the wire the current density reaches the value corresponding to point A on the curve of Fig. 1. As the voltage increases, the point at which current density equivalent to A exists, moves out from the surface of the wire to a point x within the insulating material. At this moment the insulating material between a radius R and radius x is carrying a current density corresponding to a point beyond the point A on the curve and we will say for the moment that the current at the wire surface corresponds to the point B when the current density at radius x corresponds to point A. Until the current density at the surface of the wire reaches a value greater than that density corresponding to point B, there is no part of the insulating material in which the conducting path is operating with a negative voltage current characteristic. The part from radius x to radius R is still operating at a current density corresponding to points somewhere between 0 and A on the curve. The result is a stability of the insulating sheath.

At this point, if the voltage is increased, the radius at which the current density corresponds to the point A will move farther towards the sheath. The radius at which the current density corresponds to point B will move out from the conductor surface into the insulating material. We will then have in the insulating material three zone conditions:

1. The point from radius x to radius R corresponding in current density to points between O and A.
2. A distance from radius x to radius x_1 carrying current densities corresponding to the part of the curve A-B.
3. Portion of the material from radius x_1 to the conductor surface in which the current characteristic has become negative and corresponds in current density to the part of the curve beyond B.

If at this point the total voltage current characteristic of the path from the conductor to the lead sheath is still positive, the insulating material is in stable equilibrium and breakdown will not result. However, the moment the composite voltage-current coefficient of the path from the conductor to the lead sheath becomes negative, the current begins to increase rapidly and the insulating material will be destroyed by heat. This is the so-called puncture voltage and is really not a puncture voltage but is a voltage at which with the given material and spacing, the composite volt-ampere coefficient of the path from the conductor to the sheath becomes negative.

The current herein discussed is the pure conduction current such as would be produced with the application of direct-current voltage. The capacity current flowing under alternating voltage serves merely to raise the temperature of the insulating material. Due to the negative temperature resistivity coefficient of many insulating materials however, this capacity current has a very decided effect on the voltage at which the current density in the insulating material becomes great enough to destroy the material by heating. This explains certain of the discrepancies in alternating and direct-current breakdowns of insulating materials. Under this theory also the effect of time of application of voltage in the breakdown voltage becomes apparent as merely the time element of an energy function.

It is well known that gaseous conduction presents characteristics of a conductor of the class described and that this conduction is an electronic or ionic migration. In a solid insulating material the ionic motion is restricted, but there is an enormously greater supply of electrons or ions available and it seems an entirely tenable theory that this conduction in materials of this class is electronic or ionic in nature. Viewed in the light of this hypothesis, Mr. Peek's Energy Distance Theory acquires wider meanings and the ratio of $\frac{D}{d}$ equals 2.72 takes on a rather definite meaning. Our older theories of the mechanism of a breakdown of a dielectric have led to contradictory theories and ideas and the mass of data that have been accumulating does not seem to admit of explanation throughout the entire field without rather startling hypotheses and exceptions being made.

I cannot accept completely the theory of an over-stressed dielectric still carrying a certain amount of voltage gradient by some mysterious virtue of its geographical position. When we examine this phenomena under the light of the above discussed hypothesis, a certain amount of light seems to be thrown on some of our more serious problems in the insulation field. I should be very glad to have others who have been studying this field examine this hypothesis critically as I believe there is some merit in the theory and considerable evidence to support it, especially from our researches of recent periods.

F. Fernie: The writer is greatly interested in Mr. Simons' interpretation of his (the writer's) experiments.

The conception of an over-stressed dielectric still carrying its share of the voltage is new to the writer, and he is inclined to abandon the "skin-resistance" theory in favor of it. Indeed the "skin-resistance" theory was only presented for want of something better. It has been suggested as a possible explanation that the dielectric constant of an insulation may alter under an electric stress; the writer's informant having some recollection of experimental work done on porcelain in this connection, but the writer has been unable to trace it.

As Mr. Simons points out, the difficulty in forming a conclusion is the lack of data.

The only results the writer has been able to find are in a paper by Dr. Klein abstracted from the E. T. Z. in *London Electrician* dated Dec. 26th, 1913.

The following table is taken from Dr. Klein's paper, which deals with single-conductor paper cables.

	3 mm. thickness of insulation			6 mm. thickness of insulation		
	A	*B*	*C*	*D*	*E*	*F*
Area in sq. mm......	16	50	240	16	50	240
Minimum...........	20.0	20.0	20.0	35.0	30.0	50.0
Mean...............	40.3	36.6	37.2	56.5	62.0	70.3
Max................	49.3	49.0	54.0	70.0	84.0	95.0
E_1..................	20.3	15.8	14.3	18.3	16.1	14.9
E_2..................	25.4	20.8	17.6	23.5	20.6	19.0

There were apparently 60 to 80 tests made on each size cable. The figures in the first 3 columns are the breakdown values in kv.: E_1 and E_2 are the maximum stresses at breakdown calculated from O'Gormans' formula (E_1), and Deutschs modification (E_2), in kilovolts per millimetre.

The minimum stresses calculated from Klein's E_1 figures are:

A	8.8	*D*	5
B	8.9	*E*	6.3
C	10.5	*F*	7.9

These figures are inconclusive, as is to be expected, when there is such a big diversity between the maximum and minimum values found for similar samples. Still by making a selection from Klein's figures, a good case could obviously be made for a constant minimum stress. Mr. Simons attributes such diverse results to "the inherent lack of uniformity of insulating materials." The writer disagrees with this view, and regards non-uniformity as ultimately a *surface tension* effect.

Probably everyone is familiar with an experiment by which potassium permanganate solution can be filtered with blotting paper so as to emerge nearly colorless. The same effect tends to take place in the impregnation of paper cables. If the paper is wound on rather tightly so that the compound is forced to go through the paper, rather than between adjacent layers, analysis will show that the compound which reaches the inner layers of paper is different from that on the surface layers. There are then a variety of reasons for non-uniformity: (1) Tension with which the paper is lapped; this may be varied in several ways, during the lapping of one length of cable. (2) Variation in the mixing of the compound ingredients; possibility of different phases; as solution of *A* in *B*, or solution of *B* in *A*. (3) Age of the compound, *e. g.* time elapsing since mixing and amount of stirring done. As is well known spirit varnishes are particularly sensitive in these respects. (4) Temperature of compound.

It may be concluded then that paper cable making is by no means an exact science, and cable makers are unable to predict exactly what the breakdown of a particular design will be, even from the purely empirical data gained from experience.

Returning now to the minimum stress theory the writer, reasoning from the behavior of concentric electrodes, concluded that the breakdown voltage between two adjacent conductors would depend on the stress on the insulation situated midway between them. He evolved the following formula for the breakdown voltage:

$$V_{rms} = \frac{K\left(2rx + \frac{x^2}{2}\right)\log_e \left\{\frac{x+2r}{2r} + \sqrt{\left(\frac{x+2r}{2r}\right)^2 - 1}\right\}}{\sqrt{x^2 + 4rx}}$$

x is the thickness of insulation between conductors, and r is the radius of the conductors. K is a constant for any one kind of dielectric. (In one series of tests with paper $K = 39$).

This formula has given fairly accurate results with some kinds of insulation, but the writer has not made nearly enough experiments to justify him in presenting it as "Highly probable." It is given here as of possible interest in connection with Mr. Simons' paper.

L. L. Perry: Mr. Roper shows, in Fig. 12, values of "Dielectric Loss Assumed for Purposes of Calculations." His method seems an excellent one and on comparing with his assumptions the results of tests made on some recent 3-conductor cables of 400,000 cir. mils used on 13,200-volt circuit, I have thought the results might be of interest to the Institute. As will be noted by accompanying curve, Fig. 2, at temperatures above 85 deg. cent. Mr. Roper's assumed characteristics give somewhat higher values than these tests show, and so are on the safe side. At temperatures below 85 deg. the tests on all but cable *C*-2 also show lower values than in Fig. 2 of Mr. Roper's paper.

It is thought Fig. 3 which gives the average power factor for each of the four cables tested, may be of interest, as presumably this should be about the same for different sizes of conductor at the same temperature.

In these tests the power factor curves when plotted to the arithmetical-logarithmic scales, as shown, follow closely the shape of the loss curves.

The power factor at any definite temperature varies but little with a change in voltage from 7000 to 17,500 volts, the variation above 85 deg. cent. from the average having a maximum of about 8 per cent, and below 85 deg. cent. about 25 per cent. These are similar to the results in the power factor figures given in Clark and Shanklin's, A. I. E. E. paper of June, 1917.

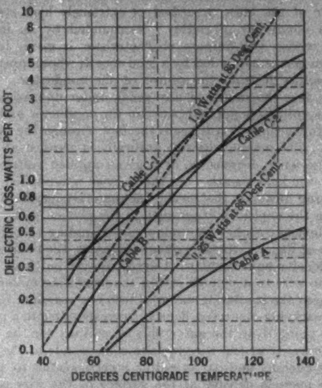

FIG. 2—DIELECTRIC LOSS FROM TESTS ON THREE MAKES OF CABLE COMPARED WITH ASSUMED LOSS

400,000 cir. mil., 3-conductor cable, 7 ft. 32 in. x 7 ft. 32 in. paper insulation—13,200 volts, 3-phase tests. Cables *C*-1 and *C*-2 of same make.

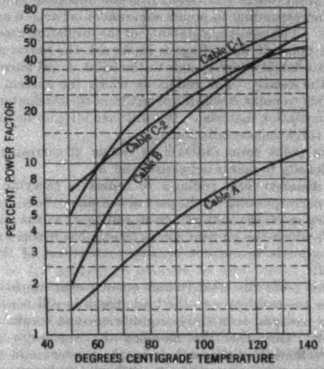

FIG. 3—AVERAGE POWER FACTOR OF DIELECTRIC LOSS IN TESTS

400,000 cir. mils., 3-conductor cable, 7 ft. 32 in. x 7 ft. 32 in. paper insulation—7000 to 17,500 volts, 3-phase tests. Three makes, *C*-1 and *C*-2 of same make. Note: Above 85 deg. cent. the tests showed a maximum variation in power factor at any temperature of only about 8 per cent from the average shown for voltages from 7000 to 17,500. For temperatures below 85 deg. cent. the maximum variation was about 25 per cent.

W. A. Del Mar: Dynamo-electric machines and transformers are now susceptible of design with wonderful exactness. Designs made to any performance specifications would differ but little whether made by one manufacturer or another, and the performance would fulfill predictions with very little margin of error. This is because the theories of the magnetic circuit, of electromagnetic induction, and of the generation and flow of heat, are well understood and their bearing upon practical design are appreciated.

It is not so with electric cables whose insulation has seemed to us as capricious, in its behavior, as the magnetic circuit must have seemed to dynamo designers in the days of the long-pole Edison dynamos.

It is hoped that this symposium will be the starting point for research which will be as epoch-making as Hopkinson's work on the magnetic circuit, which put dynamo design upon its present basis of exactness. The papers which have been presented do not record any startling discoveries, but taken in the aggregate, they show that cable engineers are alive to the problems before them and that both manufacturers and operators are closing in upon some basic facts and devising ingenious theories that may lead eventually to the solution of the major problems.

While not part of this symposium, Dr. K. W. Wagner's recent Institute paper should be studied in connection with the present group.

It is interesting to note that two papers are devoted to theories of dielectric loss; that they are both based upon imaginary microscopic views of the insulation, which reveal a heterogeneous structure, and that both blame the dielectric loss upon this heterogeneity. The two theories differ in that in one, moisture particles are held to be the culprits, whereas in the other, the impregnating compound is blamed.

There is no doubt about the fact that moisture was to blame for the high dielectric loss of many of the cables of years ago. These cables were not thoroughly dried, both the paper and the oil containing moisture in considerable quantities. The power factors of such cables, when plotted against oil resistivities, do not lie anywhere near the theoretical curve in Fig. 3 of our paper. For example, an oil resistivity of 0.5×10^{12} ohm-cm. corresponds to a theoretical power factor of 5 per cent at 85 deg. cent. A cable with about 2 per cent moisture, as derived by vacuum dessication at 130 deg. will have a power factor of about 18 per cent. The water, in such a case, is the principal factor determining dielectric loss. In our paper we expressly state that in applying the theory it is assumed that practically no moisture is present, as a very small proportion will have a greater effect than even a fairly large reduction in the resistivity of the oil or cellulose. Our theory is intended to explain that element of the dielectric loss which occurs in a well-dried cable, and it has been found to be so reliable, as a working guide, that we can confidently state the power factor of every length of cable made in the factory merely by making resistivity tests of the oil. Since the writing of the paper, an experimental point has been obtained for Fig. 3 corresponding to a resistivity of 6×10^{12} ohm-cm. The theoretical value of the corresponding power factor was 2.04 per cent; the experimental value was 2.1 per cent. We are pleased to note that Mr. Shanklin's views support our own.

We may thus claim to be able to scientifically design cables for power factors. Having accomplished this, our next step was to try to design for dielectric strength. The first obstacle to be encountered was the lack of formulas to express a relation between the dielectric strength of the insulation and the breakdown voltage of a cable. A fundamental difficulty stood in the way; the apparent dielectric strength of flat samples varied with their area and thickness. Dr. Wagner came to the rescue with his mosaic electrodes, which enabled true dielectric strength to be measured. Knowing the true dielectric strength of the insulation how can the breakdown voltage of a cable be calculated? Mr. Peek has given a working solution in the case of single-conductor cables which may be expressed by the formula

$$E = 2.3\,S\,(\,r + 1.1\sqrt{r})\log_{10}\frac{R}{r}$$

Where E = breakdown tension, kv.
S = dielectric strength, kv./cm.
R = outer radius of insulation, cm.
r = inner radius of insulation, cm.

In the case of triplex sector cables which we have tested

$$E = 0.9\ St$$

Where E = breakdown voltage between conductors, kv.
S = dielectric strength, kv./cm.
t = thickness of insulation between conductors, cm.

With the same kind of insulation, these two formulas give about the same value of S. Our own experiments confirm Mr. Peek's formula far more strikingly than the experiments cited by him. For example, twelve single-conductor cables having r = 1.04 cm. and R = 2.67 cm. broke down at an average of 200 kv. the same value being attained at 25 deg. and 85 deg. cent. Mr. Peek's formula also gave 200 kv.

Some experimental data published by Dr. Klein in the E. T. Z. and abstracted in the *London Electrician* of Dec. 26, 1913, show a much more uniform stress at the energy distance suggested by Mr. Peek than either at the conductor surface or the sheath surface.

Equipped with these formulas the next step was to find the factors upon which the value of the dielectric strength S depends.

The ion-baffle theory was applied in the following way. The dielectric strength of impregnated paper insulation in a cable may be expressed by the following formula:

$$S = S_o\,BF$$

Where S = dielectric strength of impregnated paper in cable,
S_o = dielectric strength of oil,
B = factor expressing baffling effect of paper,
F = factor expressing variations other than those affecting the factor B. (Principally factors affecting the formation of vapor pockets.)

The range of variation of the above quantities with ordinary commercial materials and processes is about as follows:

S_o	20 — 33
B	2.0 — 5.0
F	0.5 — 1.0

Hence, the maximum and minimum values of S would be 165 and 20 respectively, but the combination required to produce so low a dielectric strength as 20 kv./cm. would be rare. Most commercial cables run between 50 and 100 kv./cm. The stress, in this case, is assumed to be calculated by the formulas given above.

By analyzing the causes of the variation in each of these factors, it has been found possible to raise their values and so greatly increase the dielectric strength of the insulation.

I am pleased to note Mr. Shanklin's general concurrence with our theory of dielectric loss and with our conception of ionic migration in oil. While he agrees that this conception serves to explain both ordinary conduction and dielectric failure under long applications of tension, he takes exception to applying it to explain failures under short applications of tension. He cites two reasons for this point of view. The first is that cables of low dielectric loss and therefore of low ion mobility, often breakdown at low voltages on short period tests, and the second is that impregnating compound of high resistivity and therefore also of low ion mobility, often has very low dielectric strength. He argues from this that as low ion mobility does not result in high dielectric strength, the failure of insulation cannot be due to the mobilization of ions.

There is a general answer to both of these reasons, namely, that the kind of ionic mobility that constitutes the conductivity of the insulation is obviously the average mobility, whereas, that which would lead to sudden dielectric failure would be a local maximum mobility. Such a local maximum is not necessarily proportional to the average, especially in dielectrics of such complex nature as either impregnated paper or impregnating compound. There is also a special answer to Mr. Shanklin's first objection, namely, that the ionic mobility of the impregnating compound only affects the factor S_o in the above formula, whereas, the low breakdown voltage of the cables may have been due to low values of the factor B or F.

Mr. Shanklin has called our attention to a very important element in cable failure, namely, the establishment of local high-frequency surges at vapor pockets. I am inclined to believe that practically every cable that fails on five-minute test, fails from this cause, but I do not believe that a failure will start at either the conductor or the sheath because these large masses of metal would prevent any sudden local temperature rise in the insulation adjacent to them. It is generally the heating due to these surges which creates the local maxima of ion mobility referred to above.

A curious fallacy has obsessed cable makers for many years, namely, that the thickness (*i. e.* viscosity) of the compound should be so great that it will not flow in the cable. In the attempt to follow this theory, compounds have been made of heavy mineral oils thickened with resin. This theory would have been satisfactory if cables were stationary apparatus, but it neglected the fact that cables have to be bent in manufacturing, testing, installing and splicing. When a cable is bent, it is contracted on the inside of the bend and expanded on the outside. If the oil is too viscous, it will not flow from the inside to the outside of the bend, and therefore, the cable will be dielectrically weak due to vapor pockets on the outside of the bends. Cables made with oil of a viscosity properly adjusted to the paper tightness, break down at the same voltage hot or cold.

K. W. Wagner's interesting paper delivered at a Chicago meeting of the Institute this year should be read in connection with Mr. Roper's paper, as both arrive at similar conclusions from entirely different avenues of approach. In this paper, the theory is advanced that solid dielectrics fail due to their negative temperature coefficients of resistivity. If heat is generated in a filament of insulation more rapidly than it can be dissipated, the resistivity will fall off cumulatively until it is so low that the current becomes high enough to burn the filament. According to this theory, it is the slope of the resistivity-temperature curve and not the actual value of the resistivity which determines dielectric strength.

Prof. Scott has told us that a successful 25,000-volt cable was installed some twenty years ago and that we are still practically at the same stage. The cable he was thinking about was installed twenty-two years ago, and practically no important progress in cable making occurred in twenty of those twenty-two years. The advances recorded at this meeting are the product of the last two or three years and are due entirely to the progressive spirit of a few manufacturers and to the untiring efforts of a few cable users.

D. M. Simons: I believe that possibly one of the most important developments of the discussion is the emphasis laid on the negative temperature coefficient of insulation resistance by Dr. Steinmetz, Mr. Peaslee and Mr. Del Mar's quotation from Mr. K. W. Wagner. Mr. Peaslee's application of this idea to the case of concentric electrodes in terms of insulation resistance and the current density, instead of the more usual method of voltage and stress, is most interesting. I believe that even if the negative temperature coefficient is not the complete answer, it will undoubtedly have to be included in any future theory of cable breakdowns.

While my paper is not really a criticism of Mr. Fernie's article, but merely an attempt to explain one section of his data by a different theory and to emphasize the lack of true constancy of his experimentally determined minimum stresses, I was especially glad in reading the final proof of the discussion to find that he had had an opportunity to comment in writing. His remarks have been read with pleasure. Mr. Fernie's formula for the breakdown strength of a multi-conductor cable is interesting. During the preparation of this paper, the writer also developed a formula for the breakdown voltage of a three-conductor cable on the same theory as that outlined for a single-conductor cable, based on the ratio of diameter under lead sheath to conductor diameter giving the minimum value of maximum stress as calculated for triplex cables in the paper of which he was co-author in the January 1921 JOURNAL. This, however, was not included in the present paper, since the theory did not seem to be vindicated sufficiently for the case of single-conductor cables.

Many theories have been proposed. The true solution must exist, but it undoubtedly cannot be determined until the amount of available experimental data is vastly greater than at present.

J. E. Shrader: I wish to say just one word in regard to the potential gradient and the formation of corona, which, as Prof. Whitehead has said, is rather a difficult one to calculate. I do not know with our present state of knowledge, that we could calculate the potential gradient through the range which is used.

Dr. Whitehead also spoke of the abruptness with which the power factor changes in some cases and not in others. That there is a very abrupt change in some cases, I attribute to the fact that there are more uniform layers of gas. With the thinner layers it is almost impossible to have a uniform thickness of gas layer, in which case there is a gradual variation of the power factor.

I think, as Prof. Karapetoff has said, that we ought not to be afraid to tackle these problems on the ionization theory, and modern theories which are being produced. I think it is going to be a matter of getting at the fundamental data and coordinating it with modern theory which will solve all of our engineering problems.

C. F. Hanson: Referring to the Del Mar-Hanson paper, the imperfection angle is the angle by which the current falls short of leading the applied voltage by 90 deg. In a perfect dielectric the current would lead the applied voltage by 90 deg.

Other data on the relation of the power factor of impregnated paper and the resistivity of the impregnating compound have been obtained since Fig. 3 in the paper was produced. In Fig. 3 the points shown from actual measurements were obtained at 85 deg. cent. We have now obtained additional points at 70, 80 and 90 deg. cent. These points, in addition to the 85 degree points, are shown in Fig. 4 of this discussion. The points all lie very close to one curve.

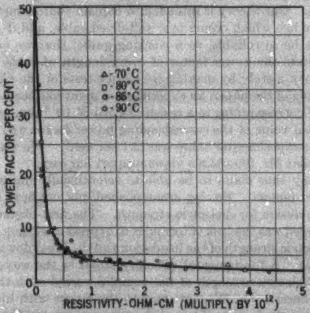

FIG. 4—RELATION OF POWER FACTOR OF IMPREGNATED PAPER AND RESISTIVITY OF IMPREGNATING COMPOUND AT TEMPERATURES 70 TO 90 DEG. CENT.

The use of the curve may be illustrated best by an example. Suppose the resistivity of a compound at the various temperatures is as follows:

Temp. deg. cent	70	80	85	90
Resistivity (ohm-cm.)	2.5	1.3	1.0	0.80×10^{12}

From the curve we obtain the power factor of paper impregnated with the above compound for the given temperatures. Of course the paper has to be thoroughly dried and impregated. The power factors obtained are as follows:

Temp. deg. cent	70	80	85	90
Power Factor (per cent)	3.0	3.7	4.0	4.5

The curve does not hold good for 60 deg. cent. or less.

Mr. Shrader has contributed some valuable information in his paper. His curves marked "1" in his Figs. 3 and 12 are very interesting. They show that manila paper saturated with petroleum jelly has a smaller imperfection angle than white India mica at stresses up to 60 kv. per cm. Ordinarily we do not think of an impregnated paper having any electric qualities superior to mica.

Referring to his Fig. 14, Mr. Shrader discusses the difficulty encountered in obtaining consistent values of power factor and potential gradient in the ionization region. We have found that one reason for this difficulty is that when ionization is reached the deflection of the wattmeter is a function of time of the application of voltage. Perhaps a part of the difficulty could be overcome by taking readings after a definite period of application of voltage. The length of the period would have to be determined by experiment. It is impossible to obtain readings at the moment the voltage is applied because, even though a wattmeter is aperiodic, there is a time lag in the deflection. I submit a curve, Fig. 5, showing variations of deflections with the time of application of voltage. The readings were taken on impregnated paper at 30 kv. Ionization started at about 24 kv.

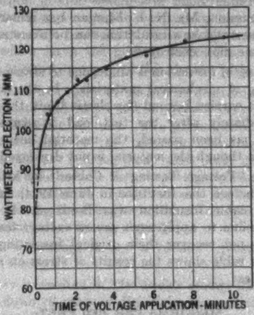

Fig. 5—The Effect of Time of Voltage Application on the Measurement of Dielectric Loss when Ionization is Present.

The first point on the curve was taken 15 seconds after the full potential of 30 kv. was applied to the dielectric. We could not obtain a reading sooner because it took 15 seconds for the wattmeter to come to a steady deflection. The reading was 90 mm. If we could have read the wattmeter the moment full potential was applied we would, perhaps, have obtained a reading of about 75 mm. as indicated by the curve. The time for building up the voltage was about 15 seconds. The curve shows the importance of allowing a definite fixed period for building up the voltage and a fixed period between the time when full voltage is obtained and the time when the wattmeter is read.

Mr. Shrader has calculated the effective a-c. resistance both from the point of view of a fictitious resistance in series with a perfect condenser and also in multiple with the condenser. If the resistance in series with the condenser be designated as r and the resistance in multiple as R, the power factor may then be expressed as follows:

$$\cos\theta = \sqrt{r/R} \qquad (1)$$

or

$$\sin\psi = \sqrt{r/R} \qquad (2)$$

where ψ is the imperfection angle and is equal to $(\pi/2 - \theta)$.

The above equation is useful in checking the calculations of r and R which have been obtained from

$$r = W/I^2 \qquad (3)$$

and

$$R = E^2/W \qquad (4)$$

The power factor is ordinarily obtained from the equation

$$\cos\theta \frac{W}{E\,I} \qquad (5)$$

Values obtained from equations (3), (4) and (5) should satisfy equation (1).

D. W. Roper: Mr. Fisher has apparently misread or misinterpreted the statements in my paper regarding the relative merits of foreign and American cables. It is my impression, based upon the results of a great many dielectric loss measurements, made for the company with which I am connected, and comparing these with the dielectric loss figures which have been furnished me by foreign engineers and manufacturers, and also by the figures quoted by Mr. Welbourn this morning, that on the question of dielectric loss the American manufacturers are not at any disadvantage as compared with the foreign manufacturers.

The figures obtained appear to indicate that the dielectric losses of the foreign cables are about on a par with the best American practise, and in fact some of the figures obtained from a few samples of American manufacture are lower than any I have been able to obtain on foreign cables, the only exception to that statement being one very special case of a foreign cable made with a hollow conductor and impregnated with a thin liquid insulation of the nature of transformer oil rather than a grease, of the nature of petrolatum, and even in that case, the loss was not materially below the best records of tests published in this country.

Mr. Atkinson made some comments on the bending test called for in the English specifications, and in the National Electric Light Association specifications. He did not mention, however, that the English specifications, although they are more severe, call for three cycles instead of two, as is the case with the American specification, but they do not permit of any tearing of the insulation, whereas the National Electric Light Association's specifications permit a maximum of two layers being torn at any one point.

As a matter of practical experience, we know that with this limitation of two torn papers at any one point, there can be scattered throughout the cable a great many other tears of the insulation, following the bending test, without there being two at any one point, and this is a radical point of difference between the two specifications.

We have found, although we have made several hundred bending tests in the last four years, that only in cases where the insulation is very poor in quality, do we find that the bending test shows any difference whatever between the test at room temperature and the test at minus 10 deg. cent. The curves shown in the paper, on bending tests, quality of paper, etc., shows that in most cases no tearing whatever results, even at the minus 10 deg. cent. test.

There is one point, however, in which the English have an advantage over the American manufacturers, and which is not brought out in this paper, and which was contributed as a part of the report of the Committee on Transmission and Distribution.

The American cable manufacturers were all given an opportunity to present their ideas regarding the thickness of insulation they would recommend for various voltages, and we also had the thicknesses published by the British Engineering Standards Association. The thicknesses recommended by the British are in general below the thicknesses recommended by the American manufacturers, and some of the latter recommend up to 25 per cent more. The English practise, however, appears, as near as we can discover from correspondence with their engineers, and from some of our engineers, who have been to England,—to use somewhat less insulation than is specified by the British Engineering Standards Association. The thicknesses which the Commonwealth Edison Company have been using in the last year or two are about the same as the British Engineering Standards Association, although we have been accused of being somewhat radical on that point. It was, therefore, of great interest to learn recently, that one of the English companies, that has been operating 20,000-volt cables for a number of years, and has had considerable experience, has, upon the basis of their own experience, and on the advice of their consulting engineers, reduced the thickness of insulation by 25 per cent on these 20,000-volt cables, so that the thickness of insulation which will be used on 20,000-volt cables, is only a trifle more than the Commonwealth Edison Company is using for 12,000-volt cables.

It is to be hoped that the investigations which the American cable manufacturers have started, as evidenced by the series of papers this morning, will continue until they are at least on a parity with the foreign manufacturers in this respect.

It is also of interest to note that apparently some of the data which have been presented this morning have resulted primarily in further investigations into the properties of cables and into the properties and desirable features to be incorporated in condensers for insulation with 60-cycle systems for improving the power factor. Private information indicates that more than one manufacturing company has a larger engineering staff investigating this subject, which is not yet in serious commercial production, than they have investigating the properties of paper insulated cables.

We are perfectly willing that the manufacturers should get information in that way or any other way, which will help them in the design of their cables.

It is also interesting to note the serious advances made in this country in the direction of dielectric losses. In looking over the guarantees received in the last few years, from the American manufacturers,—and we give them all a chance when we ask for bids—it was noticed that the maximum dielectric losses on a certain size of cable last year at a temperature of 80 deg. cent., was double the maximum figures we received this year at the same temperature and same size of cable.

It would have been interesting if Mr. Welbourn has given his dielectric loss data in power factor rather than watts, as, without knowing the size of the cable, it is difficult to compare it exactly with the other data that are available.

The calculations to determine the maximum permissible current on various sizes and voltages of cables were based on the average duct radiation as given in the Clark and Shanklin paper of 1919, and now Mr. Shanklin in a measure discredits these data, or at least casts a doubt on its accuracy for this purpose. This serves to emphasize the importance of securing more fundamental data. To obtain the data from cables in commercial operation appears to be a very difficult task due to the variations in load on the cable, but it would be of great value if some investigator could surmount the difficulties and devise a method which the operating companies could use for measuring the radiation constant of their conduits. In spite of the inaccuracies of the fundamental data as pointed out by Mr. Shanklin, we do find that for the conditions in Chicago, the figures obtained from these calculations are a sufficient guide to enable us to determine within less than ten per cent the amount of load that can be safely carried on our cables without being subject to dielectric loss failures.

W. I. Middleton, C. L. Dawes, E. W. Davis: In view of the present day tendency to operate cables at higher voltages without increasing the walls of insulation, it is of vital importance to engineers to know the actual rather than the theoretical stresses within a cable. A mathematical formula which cannot be checked experimentally should not be accepted as standard for calculating such stresses. If the formula published by Mr. Atkinson in the PROCEEDINGS of the A. I. E. E. in 1919 has been "thoroughly substantiated" as Mr. Simons says, it would be of inestimable value to engineers to have the figures published.

The design of three-conductor cables depends largely upon insulation constants obtained from tests on single-conductor cables. The relation between breakdown stresses in single and three-conductor cables is necessary to assure the proper design of the three-conductor cable.

We do not believe that the rupturing stresses in three-conductor cables are materially lower than for single-conductor cables, especially if such cables be well made. From the data of breakdown tests made by us, the stresses calculated by the old method are much more in accordance with our belief than stresses calculated by the new method.

In the discussion, Mr. N. L. Morgan has remarked that he does not understand how insulation can be overstressed and at the same time not destroyed.

The stressing of insulation is analogous to stresses and strains in the testing of mechanical materials. In the latter case, if the test is not carried beyond the elastic limit, the material recovers immediately after the test load is removed. If the elastic limit has been passed, the material never completely recovers, even though the material is not destroyed.

In a paper "Voltage Testing of Cables" by Middleton and Dawes read before the Institute in June 1914, the matter of overstressing cable insulation was discussed. It was shown that it is possible to apply such severe voltage tests to cables that they do not recover their original insulating properties. The following table shows the results of stress on some rubber insulated cables:

MEGOHMS PER 1000 FEET

Test No.	Length tested feet	Initial M. O. before voltage	Immediately after 2500 V 1 min.	Immediately after 5000 V 1 min.	2 Hours after 5000 V 1 min.	Immediately after 5000 V 5 min.	2 Hours after 5000 V 5 min.
1	1562	14,500	14,500	7,500	11,500		
2	1547	22,000	22,000	16,000	18,000		
3	3150	7,500	7,500	6,000	7,000	5000	5000
4	1740	15,000	15,000	6,500	10,000	750	2500
5	2402	15,000	15,000	7,500	10,000	2500	3500

The insulation resistance in tests 1 and 2 were considerably affected by the 5000-volt, one-minute test, but practically recovered after 2 hours. Test 3 showed the least effect of the 5000-volt, one minute test, while 4 and 5 showed rather slow recovery. An additional 5000-volt, 5-minute test apparently caused permanent injury to 3, 4 and 5, as they showed very little recovery after 2 hours.

In no case was the insulation ruptured but in 3, 4 and 5 it was most certainly overstressed.

We quite agree with Professor Karapetoff that the effects on the dielectric strength of the various elements entering into the composition of a dielectric should each be analyzed separately, in order to understand more thoroughly the nature of voltage breakdown. The papers of Messrs. Del Mar & Hanson, Du Bois and Schrader are analytical in this sense and their data and conclusions give in a degree, quantitative effects of moisture, air spaces, etc., on the ultimate properties of the dielectrics.

On the other hand whether or not the results of such investigation are correct can only be ascertained by data obtained from the finished cable, both in the factory and under operating conditions as are given in Mr. Roper's paper. Therefore even though data do not involve the individual effect of each element of the dielectric, they are nevertheless valuable.

Professor Karapetoff mentions the fact that the stresses in dielectrics, which are stressed beyond the elastic limit should not be calculated with constants derived for the material when not so stressed. Our investigations on the special cable, the results of which are shown in Fig. 5, was undertaken to determine such effects. The average effect for insulation in the interior of the cable which was overstressed was only of the order of 5 per cent at the instant of break down, a negligible error as compared with deviations ordinarily obtained with dielectric tests. This cable was purposely made with an inferior grade of rubber compound in order to exaggerate the effect of overstressing. A high-grade compound would have shown a much smaller change in permittivity. This combined with other measurements that we have made, leads us to believe that the change of permittivity of the ordinary rubber compounds under stress can be neglected when calculating potential gradients. We would expect greater changes in paper cables, as the low viscosity of the filler permits the components having the greater permittivities to seek positions in those portions of the electrostatic field which have the greater intensities. We have as yet made no attempt to measure this change with paper cables.

The pyro-electric theory of dielectric destruction presented by Dr. Steinmetz and Mr. Peaslee offers a very plausible explanation of dielectric rupture. The phenomenon of the volt-ampere characteristic of the dielectric attaining a negative slope, and the current running away must occur in a very short interval of time as otherwise the comparatively small amount of energy involved would be unable to raise the temperature to the values necessary for this phenomenon to occur, for the heat would be conducted away too rapidly.

It will be interesting to see if further investigations substantiate this theory.

We are very interested in Mr. Peek's energy-distance theory of the breakdown of gaseous dielectrics as applied to solid dielectrics. Accordingly we have attempted to evaluate constants for the series of tests given in our Tables I, II and III inclusive.

In Table I, we find that equation $g_v = M\left(1 + \frac{K}{\sqrt{r}}\right)$ gives consistent results as shown in the following tabulation.

M was found to be 116 and $K = 0.345$.

Size cond. A.W.G.	r Cm.	$0.345\sqrt{r}$	R_1 Radius to point of constant stress. cm	R Outside radius cm.	R_1/R	Stress from curve for Table I similar to curves for Table II shown in Fig. 10. Values of R_1/R same as in preceding column
24 Sol	0.0255	0.0550	0.080	0.476	0.168	300 Volts per mil
20	0.0407	0.0696	0.1103	0.476	0.232	270
14	0.0826	0.0992	0.1818	0.476	0.382	270
..	0.1140	0.1165	0.2305	0.476	0.485	270
8	0.1625	0.1390	0.3015	0.476	0.634	300
6	0.208	0.1435	0.3495	0.476	0.784	290
5	0.236	0.1535	0.3895	0.476	0.818	295
2	0.328	0.1975	0.5255	0.476	1.104	340
2 strd.	0.330	0.1980	0.528	0.476	1.11	410

It will be noted that except in the case of the two solid and two stranded conductors, the stress was practically constant at a radius R_1 from the center of the conductor.

We were unable to find any values of M and K that would satisfy Tables II and III. In fact in some instances the constant K became negative. Therefore, it would seem to us it has not yet been proved that this theory is applicable to all breakdown of solid dielectrics. Perhaps if the time of test were made very long, hence give the ions greater time to bombard the dielectric, the breakdown voltages might more nearly agree with these energy-distance equations.

Some Suggestions for Possible Improvements in Methods of Engineering Education

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Attention is call d to the fact that very few of those who take engineering courses in the colleges are fitted by previous mathematical training to take up the work properly. Suggestion, therefore, is made that all engineering courses drop back into the more elementary mathematics during the first year, in order to give a thorough drilling in the practical use of such mathematics, with a view better to fitting the students for more advanced work. It is believed that with this elementary training the students can make much more rapid progress in their advanced work, not only in engineering work, but in physics, mechanics and various other related lines.

Moreover such a course would assist the schools in eliminating those who are totally unfit for engineering work, and thus overcome one of the most serious defects of the present technical courses. The application of mathematics to practical work should be taught much more thoroughly than at present, but that appears to be impossible under the present circumstances where the students have a very incomplete elementary training.

IT may be that all real engineers are born engineers, or, on the other hand, it may be that the necessary fundamental traits are acquired *in very early childhood*. The personal experience of the writer, based upon intimate knowledge of hundreds of variously trained engineers, indicates that the real engineering traits are not acquired, to any great extent, in later childhood. But it is possible, in some few instances, that the necessary traits are present in early childhood but do not come to the front until later. However, in practically all cases of successful engineers, within the writer's experience, these traits were easily recognizable in the very early years. In fact, of the majority of the cases it might be said that the successful ones were about as good engineers at six years of age as at twenty-six, taking into account their relative knowledge and training at those respective ages. As to these traits being acquired in very early childhood, a leading engineer and educator once remarked—"The child may get some kind of a fatal twist or kink which starts him in a certain direction, and he keeps on growing that way." This is not at all unreasonable. The small boy who can "do" things or can "fix" things, naturally is called upon by his associates to do much of the fixing and mending that is required for their playthings, etc. In consequence, he gets all of the practise and becomes relatively more experienced than his playmates. The same thing may be said of mathematics. The small boy who becomes "handy at figures" is very often called upon for assistance by his schoolmates and playmates, and, in consequence, he does the helping while the others are helped and he thus gets ahead of them. Once in the lead he finds such things are easier for him and he more or less follows the path of least resistance. Thus whether the necessary traits were born in him, or are acquired in very early childhood, the natural tendency is toward cultivation, or exaggeration, of these traits through the normal activities of the child.

Two of the most valuable traits that a small child can have is the ability (1) to use his head, and (2) to use it in a more or less quantitative way. By the latter is meant that a child with a quantitative sense has a great advantage over others. Apparently this sense can be cultivated and quite highly developed in early childhood by proper direction, and here is probably where the real training of the engineer should begin. From the writer's own observations, and from discussion of the subject with many others, he is firmly convinced that one of the best trainings that the child could have is the old-fashioned kind of "mental arithmetic." This seems to have been largely abandoned in recent years, due doubtless to the inability of the teachers to handle it properly. Mental arithmetic, if properly taught, develops quickness in thinking, and also a quantitative or numerical sense which is of utmost value in later years. In fact, a numerical, or dimensional, or quantitative sense, whatever you want to call it, if highly developed, is one of the greatest assets that an engineer can have, and it is doubtful whether this sense can be acquired properly except in comparatively early years. The man with a quantitative or numerical sense can see relationships and can reason from cause to effect to a degree, in some cases, which seems uncanny to one not possessing this trait.

Obviously, therefore, one of the first great errors in our engineering education is the improper or insufficient training in the earlier years, and it is impossible to estimate what an enormous handicap this puts upon the colleges. The earlier training too often tends to suppress imagination and independent methods of thinking. The child is taught to do things by rule, and if he happens to develop, through his own originality, a new method of solving a problem, for instance, in his school work, far too often he is criticised instead of being commended. The arbitrary methods of teaching by fixed rules, by some incapables in our public schools, is one of the curses of the country. The old-fashioned country schools with a single teacher who handled the entire work, quite often developed

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stronger mentalities than the modern supposedly much higher class schools.

It must be, and probably is, well recognized that the colleges can only cultivate existing traits, but cannot create new ones. As a prominent educator once said, "You can hatch only a gosling from a goose egg." The colleges, therefore, are handicapped in attempting to create traits and characteristics, in many cases, where such do not already exist. They are asked to build engineers out of non-engineering material,—an impossible task. Even with the modern supposed improvements in the public schools and high schools, the requirements of good engineering material, as far as the colleges are concerned are worse than they were some years ago, simply because of the enormous growth of the college population within the past few years has brought in many men of less suitable characteristics and traits than in former years. It has seemed to the writer that, many years ago when engineering education was less popular than at present, a fairly large percentage of those who sought an engineering education were men who had the "urge" or "call" for such work. Very often these were men who recognized that engineering was their life work, and who realized quite fully that an engineering training would be of great assistance to them. Such men very often were the outstanding younger men of their generation. Such men are also to be found at present, but it is questionable whether they have grown in numbers proportionally any faster than the total population of the country, whereas the technical school population has grown probably ten times as fast. If such assumption is reasonably correct, then the technical schools are being very greatly diluted, or adulterated, by those who may be classed as the unfit, in the true engineering sense. If such is the case, engineering education is bound to be on the down-grade sooner or later, unless steps are taken to correct the evil. The insolubles, so to speak, must be precipitated. Here is a truly big problem. The unfit in engineering may be the fit in something else and naturally we do not wish to prevent any one from getting a college education when he really desires it. At the same time those who "belong" in a given technical course should not be handicapped by those who do not belong. Otherwise, as the writer has stated repeatedly in the past, the training tends naturally toward mediocrity, for the poorer men are a drag upon the better ones. In fact, if the course is laid out for the average man, the less able students will have to work much harder than the better ones, whereas the more capable students, or those of stronger mentalities, should be the ones who receive the most drastic training, for our future engineering development depends very largely upon them. These should be trained to the utmost, and this is not possible, with many of the technical courses, as now constituted. This condition is well recognized in many of the schools and various attempts are being made to rectify it. As one prominent professor stated recently,—he has arranged his courses in two sections, one of which embodies the "slow freights" and the other the "fast expresses." In the former are included those with insufficient ground-work, or who are not capable of keeping up with the latter division. If any student in the "slow freights" is able to speed up sufficiently to keep pace with the "fast expresses" he can be transferred. This arrangement is an incentive to the better class of men, and, to a certain extent, removes the handicap previously described. Other schools have proposed so called "professional" and "non-professional" courses. The professional courses would take in those who have real aptitudes for engineering, while the other would include young men who desire a technical education for general purposes, but who have no strong call for true engineering.

As stated at the beginning of this article, the necessary traits of the real engineer are usually to be noted in early childhood. This should really form one of the deciding points in selecting those who should take the better engineering training, or who should be given the preference in such work. Such traits, along with a certain amount of mathematical skill and ability are necessary in real engineering, and, therefore, these should be given preference in the decision as to whether the young man is to take up an engineering course or not. This brings up the subject of mathematics, upon which something pertinent can always be said.

As has often been said in the past, one of the principal weaknesses of the engineering students lies in their inability to *use* ordinary every-day mathematics. Here and there one or two can really use their mathematics in a common sense way, but such cases are quite rare, based upon personal experience with large numbers of especially selected college men. Such criticism has often been made, but, in itself, does not help materially except to call further attention to what is already fairly well known. The writer is now going to suggest a partial remedy, which many educators may consider as unduly radical and a big step backwards, but which, in the end, should mean greater progress in the right direction. A step backward is all right at times, especially in those cases where one is going in the wrong direction; and, apparently, at present, many of the college courses are going in the wrong direction in their mathematical training.

The suggestion is embodied in the following: A great majority of the college men, in the technical courses, have had their preliminary training in algebra, geometry and trigonometry in the high schools, and such training as experience shows, is totally inadequate as a basis for the future work of the engineer. It is inadequate largely from the fact that only one student in possibly twenty-five ever sees or is shown any real use for algebra and trigonometry. It is a study with him purely, and real practise does not enter. This condition is more or less inherent in the high school training, and such training, therefore, should not be accepted as a basis or foundation for future solid technical training. The suggestion is this,—that the engineering courses in college, especially the mechanical and electrical engineering courses, *should drop back one year in their mathematics.* This suggestion may raise a cry of protest, but nevertheless, it will appear that in the long run this dropping back is more imaginary than real. What is meant is that the first year in college should take up again the purely elementary algebra and trigonometry, as now covered by the high schools, but with the difference that this first year's work should largely consist in *the application to practical problems.* If the student cannot learn to *use* algebra and trigonometry practically and skillfully, in their elementary forms, he cannot expect to use them intelligently in their more advanced forms, such as in the calculus and other work. Therefore, as said before, this first year in mathematics should be expended largely in purely elementary algebra and algebraical trigonometry, involving the necessary small amount of theory and a great deal of practise in the form of various problems. These problems should be of such a nature, in many cases, that the elementary algebraical and trigonometrical expressions are not already formulated, but the problem should be of a descriptive nature, requiring the student to develop or formulate his own equations. Herein lies a great weakness of the students. Many of them can handle equations already set down for them, by following certain fixed rules which they have learned, (this is the mechanical part of mathematics) but many of these same men cannot possibly formulate the problem in the first place.

The result of this teaching would be far reaching. In the latter half of the freshman year, for instance, the class could be led gradually into more difficult problems, involving more advanced algebra and trigonometry of a practical nature, and by trigonometry is meant analytical or algebraical rather than simple plane trigonometry. In this way the student can gradually be led into the more difficult work by easy stages and he will acquire, if he is at all capable of it, a broader understanding of the general principles of elementary mathematics. He will build up a foundation for his future mathematics especially from the practical standpoint,—and engineering primarily is built upon practical mathematics.

In the teaching of practical mathematics, however, a distinction should be made between what one of the writer's old-time professors used to designate as "mathematical gymnastics" and "horse sense mathematics." By the former he meant the kind of mathematics where everything was carried into mathematical formulas, ofttimes of more or less complex nature, when the use of a little "horse sense" would have allowed the result to be obtained directly with no equations whatever. Such spectacular exhibitions of mathematical symbols are too often considered as the primary object in view. Too often also, the actual result which is striven for, is entirely hidden by the mathematical machinery used in producing the result. The students should become imbued with the fact that their mathematics are simply attacking tools or weapons and that an exhibition of the tools themselves is not of first importance. They should also be taught to understand that really good mathematicians very often can, and do, reach the desired results with but little or no evidence of the merely mechanical part of their work, and that mathematics really must be considered, in general, as simply a very effective mechanical aid to our methods of reasoning. For instance, one can take a physical fact and express it in mathematical symbols and then by rigid mathematical operations may transform the formula into some different one which expresses another physical fact. The mathematics here represent simply accurate or rigid methods of reasoning from one fact to another related one.

Returning to the subject, an important result of this first year's training would be that it would assist the teachers to separate the capable from the incapable, in the engineering sense. Those who prove totally unable to grasp the practical application in the early and easy stages of the work could then be weeded out, so to speak,—that is, they could be transferred to other courses where practical mathematics are less needed. Those who are mentally capable in practical mathematics but who have had a very poor foundation in their previous training, would have an opportunity to catch up and thus would suffer no handicap in their later work. This would be a great step in the right direction, and one of the great advantages which would accrue from such training would lie in the weeding out of the unfit from the engineering courses proper, as stated before. This would be a very great step in advance, as it would remove the present great handicap which the lagging classmen impose on their more advanced fellows.

It was suggested, as a first step, that the engineering schools drop back a year in mathematics. However, upon reaching the second year in the engineering classes, it is the writer's opinion that the survivors of the above first year of training could handle their mathematical subjects, as well as physics and other subjects, in so much better manner that, by the end of the second year they would actually be farther along mathematically than with the present course of training, due to the fact that the fundamental training is so much better. Unquestionably with a training of this sort, those who take up studies requiring analytical work of a mathematical nature, for instance, would obtain a far better grasp of the subject, and in many other engineering subjects they would tend to get at the fundamentals far better than is possible under the present training. With such a course of training, the average engineering student, by the end of his senior year, should have a far greater practical sense than he has at present, due to the fact that his knowledge of physics, mathematics, mechanics and electrical phenomena, would have a foundation of practical mathematics. In the writer's experience with large numbers of the higher grade college students, he has found that nothing tends to develop their active thinking powers like practical or applied mathematics. This teaches them to think accurately and rigidly; it teaches them how to formulate general statements in concise form; it teaches them how to pass more directly from cause to effect; and it shows them how to pick out defects in their own reasoning and analysis, whether it be of a mathematical nature or otherwise. In other words, a good practical mathematician does not appear to be able to "fool himself" into thinking certain things are so or not so, as easily as is the case with other kinds of people. Again a mathematical mind, of a practical nature, has the ability for bridging across between apparently disconnected points and for obtaining short cuts to results, such as are not possible with other types of minds. This is why the writer argues so strongly for practical mathematics as a basis for true engineering. Men so trained possess tools which enable them to obtain quickly and accurately, results which others can only reach by roundabout methods as already said in other words.

In the proper engineering education, other lines of endeavor than mathematics are also needed, in order to broaden a man, but one essential ingredient is a broad fundamental training in practical mathematics, and without this it is hard to see how a high grade technical education is possible. Without this, schools may turn out *engineers in name*, as is so often the case, but *engineers in fact* cannot be turned out without a working knowledge of mathematics, which, as already said, is to a great extent the basis of all engineering. Therefore, let us put more work on this part of the foundation in order that the whole structure may be more substantial.

Discussion

For discussion of this paper see note, page 639.

Education

BY S. E. DOANE
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The author points out that a college course should turn out men who have acquired habits of clear thinking, concentration, perception, observation, and decision. These men should have some knowledge of the details of the subject on which they plan to specialize in later life, but this knowledge is purely incidental and is acquired in illustrating the broad principles which are useful in all phases of engineering education. It doesn't really matter much on what a young man thinks he will specialize when he leaves school, if he has clearly in mind that the purpose of education is to train his mind to enable him to acquire as much fundamental knowledge as possible, and also to acquire an incidental knowledge of the specific applications of such fundamental knowledge.

The obvious point to the paper is that mental training is the principal thing, assuming, as a matter of course that physical and moral training are sufficient to physically support an active mind.

The man has well begun his education who has acquired the inclination and the ability for self study and development, and who graduates with the thought that he has merely begun a lifetime of self education. His college education has served its purpose if it has given him a good start.

The author suggests that the instructors in our colleges should be given an opportunity thoroughly to acquaint themselves with the industry for which they are training men by spending one year out of three in industry, the other two years to be spent in teaching.

THE chairman of the Educational Committee of this Institute, Professor Magnusson, has invited me to define my views on Engineering Education. He has suggested that, "if engineers would * * * frankly state their views on the training or lack of training given engineering students, and offer constructive suggestions for improving the college trained engineer, much of value might be gained."

During my thirty-five years in the electrical industry, it has been my privilege to know several hundred college men. Many of these came to work in my department directly upon their graduation. Practically every engineering school in the country contributed its quota. My long association with these men has led me to form certain opinions regarding the training they received, and the training which I think they should have received, which I shall attempt to outline in this paper.

The purpose of education is to cause the person who is being educated to acquire experience of others.

Generalities of the character which must be considered in a paper of this sort can only apply to men who are normal physically, morally and mentally. It is my observation that those who stand high in all these qualities will do best as engineers.

I would, therefore, if I had charge of the destinies of the average college, aim to so sift out my applicants that the majority of my students would be men above the average in these three fundamentals.

I would eliminate those who are weak in any one of the three fundamental requirements without regard to their strength in other qualities. Mind you, I am talking now about the general engineering training. There are many men who are weak in body who can qualify for brilliancy of effort and become highly trained specialists. In my judgment, these men find no place in a standardized program. If I were considering how best to educate a particular individual who was weak in any one of the three, I would never advise him to take a general course of engineering. He might, however, become a great success in life in some highly specialized effort because of very superior mental attainment. Let us assume that we are training the average engineer and that he is well balanced physically, mentally and morally.

The college should perform six functions. It should offer directly:

1. Instruction in engineering knowledge. This might be subdivided into the teaching of
    a. Fundamentals
    b. Specific applications.
2. Instruction in non-engineering subjects, such as English, Economics, Law, etc.
3. Instruction and training in hygiene.

It should also make adequate provision for:

4. Inculcation of habits of clear thinking, concentration, persistence, observation, decision, imagination, etc.
5. Infusion of principles of fairness, unselfishness, tolerance, refinement, courtesy, etc.
6. Formation of friendships.

Obviously, no special courses to teach clear thinking, concentration, persistence, observation, decision, etc., can, or need, be given. It nevertheless appears to me that these qualities should be taught. This may seem paradoxical, but what I mean is this. Every instructor, in teaching a subject, knows that he is teaching more than just that one subject. He knows that he is also conveying lessons in perception, efficiency, decision, and so on, as a part of the more specific study. For example, in teaching drawing he emphasizes accuracy, neatness, observation, etc.

The point I want to make is that emphasis, during the regular course of study, should be placed upon the characteristics which contribute so largely to the future success or failure of an engineer. If the instructor will always bear in mind that he is teaching more than the facts or principles involved in a particular subject, he will do much to mould his students into efficient and productive contributors to the common good.

In addition to the "concurrent courses" in the class room, it would seem that a great opportunity exists to develop these qualities during physical training. It is apparent that many of the sports which are so popular in this country (and which I believe have contributed toward making the American what he is) are capable of developing these habits. Take tennis, for example. Tennis will develop promptness of decision, quickness of thought and concentration. Indeed, the game cannot be well played unless the player possesses these qualities to a marked degree.

Many of these things which have just been said also apply to the infusion of principles of fairness, unselfishness, tolerance, refinement, courtesy, etc. The instructor must stress these qualities at all times, but the greatest training will come, not from the instructor, but from contact with one's fellow students. It will also come indirectly from better developed minds and better developed bodies. It will come from the exercise of the qualities which were previously mentioned—observation, decision, concentration, etc. It is obvious that a man with a well developed sense of observation and perception will very easily learn what is proper in the way of courtesy, refinement, tolerance, etc. A man who can think clearly is not likely to be bigoted, or unfair.

The sixth value of a college education lies in the opportunity it offers for the formation of friendships. This needs no special reservation of time in the college curriculum. The constant association with fellow students, the common purpose, the similarlity of ideals and ambitions, a school spirit—all these go far toward making college friendships lasting and sincere.

We are now left with the problem of dividing the student's time and effort among engineering instruction, non-engineering instruction, and physical training.

My experience has led me to believe that a person's physical characteristics play a great part in what he can, and will, do. If they are good they serve as accelerators; if they are bad, they are handicaps.

It would seem to me that such time should be devoted to physical training, hygiene, etc., as would best meet the needs and requirements of the normal or average college man. This is a rather vague statement but I hesitate to make it more specific.

I do believe this, however, that more physical exercise, by a great many who are now in college, would result in great benefit. There are many students who are so intense in their desire to acquire knowledge that they cram their minds at the expense of developing their bodies.

Having allowed time for exercise and recreation, how much time should be allotted to non-engineering instruction and how much to engineering? How much of the latter should be devoted to fundamentals and how much to special applications?

Broadly speaking, I would say that the college man should have sufficient non-engineering training to enable him to express himself clearly (both orally and in writing); to give him a fair knowledge of economics—of the principles which govern our daily life; to offer him at least a speaking acquaintance with the laws by which we are governed in our relations with our fellows. He should be taught the principles of ordinary business, such as the rudiments of accounting, methods of computing costs, etc.

This may seem to be a large assignment, but such a program of non-engineering education should not be allowed to consume very much time. It is not necessary to go into any of these subjects very deeply. It is sufficient to touch upon their more important features.

Some of this non-engineering education may be obtained in connection with the engineering courses. Clear expression and good composition should be as definitely required in written work on any engineering subject as knowledge of the subject itself.

The greatest problem in allotting time and effort among the various aims of the college engineering education arises in considering whether fundamentals, or specific applications, should be emphasized.

Some claim that a good knowledge of the fundamentals of a subject (though not necessarily the most thorough kind of knowledge), followed by a thorough training in typical applications of these fundamentals, will be of greatest benefit to the student. They claim that the knowledge of certain specific applications of the fundamentals in practise will enable the student, by analogy, to best meet his needs in later life.

Others, and I believe they are now in the majority, believe that a very thorough knowledge of the fundamentals involved in engineering practise, and less acquaintance with the applications which have been made thereof, would be preferable. This is my belief.

The stressing of application leads to specialization. No student really knows exactly what he will do after he leaves school. Those who specialize while in school may find themselves doing something entirely different within a short time of their graduation. As the result of specialization many discover that studies which they had neglected, because they did not consider them of practical value in the field they intended to enter, were really of the utmost importance and value in the field they really entered.

In reading over the suggestions summarized by the chairman of your committee, Professor Magnusson, it seems to me that many of us expect too much from the immature youths from our colleges.

In all of this summary the reply of Mr. Lamme is most directly parallel with my own judgment. It seems to me that there is only one of the three fundamental assets that we can hope to find fairly well rounded out. A man reaches physical maturity at an earlier age than he will reach either his moral or mental maturity.

He should be physically fit and should know how to keep himself fit when he graduates.

He should be well advanced toward his moral maturity and should be well grounded in his habits to the end that he will maintain a high moral standard.

His mental equipment will be the farthest from development. When he graduates I think he should have the following mental qualities:

He must know how to study and should face the fact that he must be a student, throughout the remainder of his life,

a. Of knowledge
b. Of mental technique.

Under "a" he must know the fundamental laws and statements of fact of physics and chemistry. The so-called laws which an engineer must learn are, many of them, beyond explanation and must be accepted as statements of fact. Quantitative ratios must be understood. For illustration, a man should know broadly the qualities of materials, ratios of speeds, and the values of time in the quantitative sense.

My feeling is that while specialization in college avails little and that to attempt to teach a man in college anything specific, such as to design generators or motors, is almost useless, at the same time the principles of design can be taught as illustrations of the use of fundamental laws. At the time the man is acquiring his acquaintance with a law he also is obtaining a useful and sufficient illustration of its application.

I believe all specialization should come after graduation.

It is my belief that it will be found to be impossible to so define courses of study that we shall feel that our problem has been solved without approaching it from quite another angle.

I think that we will ultimately agree that these courses must be laid out understandingly by the educators themselves. How can these men do this without some experiences similar to our own?

How can these instructors, these teachers who have had no practical experience, plan to teach their students the things which those students will most need after they leave college, the knowledge which will be of greatest value, the details which will be of most use? How can they train their students best to meet the problems they will encounter, and the obstacles they will have to overcome, after they leave school, if they do not have clear ideas as to the form and character which these problems and obstacles will assume?

Thoughts of this kind have led me to suggest to several of my friends, who are directing educational work in colleges, that we should take these college instructors into industry for a period of time.

There are laboratories—excellent laboratories—in many of our large industries throughout the country, and upon the staffs of these laboratories are to be found some of the most eminent scientists and engineers in their respective lines. They are constantly at work seeking to add to existing knowledge. They are making important discoveries.

The plan which I have in mind—which is in an unfinished form, and which I know can bear much development—is roughly this. I suggest that the instructors in our engineering schools spend one of every three years in industry. Place these men in the laboratories of our great industries, in their research departments, in their engineering departments, in their manufacturing departments, perhaps in their commerical departments.

Allow them to acquire an intimate knowledge of the application of fundamentals in every field. Acquaint them with the latest methods and means by which these fundamentals are utilized in actual practise. Permit them to breathe the atmosphere in which their students will later have to work. Give them an opportunity to acquaint themselves with the actual requirements which will be expected of the college man. Introduce them to the general nature of the problems with which their students will have to deal.

If the instructor can learn all these things, I am quite sure that the men who are sent out from the engineering colleges will be benefited beyond measure.

As I think of this proposal, I can conceive that the National Lamp Works might be able to use one college instructor every year, who would obtain a thorough acquaintance with modern practise in electric lighting and allied fields while earning his salary at productive work.

At the end of three years the instructor, who has spent a year in the electric lighting industry, followed by two years of teaching, would be released to devote a year to some other industry related to the subject he teaches. Three years later he would go to still another industry, or branch of industry, and so on.

During all this time, the instructors will learn to view the subjects they teach from new angles. They will become better able to emphasize the importance of any particular phase that their industrial experience has shown them to be important. They will be able to observe their own work in more accurate perspective, and their results will be of correspondingly greater value.

It may be argued that an acquaintance with one particular industry once in three years will not enable all, or even most, instructors to keep up with modern practise in that industry. It is my thought, however, that the men who return from a year's experience in industry will convey their impressions, and will impart their new knoweldge to their colleagues.

The acquaintances which these instructors obtain during a year in business will continue throughout a life time. Through these they will maintain a very desirable contact with the field.

A procedure, such as the one I have so roughly outlined would probably have to be worked out over a period of years. As I have said, it requires consideration by those who are in intimate touch with the deficiencies which it is desired to remedy. Perhaps I am too optimistic of the results which it may accomplish. Possibly the same results may be obtained by other, and more desirable means.

In any event, my suggestion is offered for whatever it may be worth.

Discussion

For discussion of this paper see note, page 639.

Principles of Engineering Education

BY PHILIP TORCHIO
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The college training should be directed to imparting to the students the fundamentals of all physical sciences. Elementary calculus and analytical geometry should form the ground work to equip the pupil with the tools for analytical study of the problems of engineering applications. Laboratory work and drawing serve to solidify the theoretical ideas. The sound study of a foreign language is of vital importance to broaden the education of an embryo engineer. Any course of study that disciplines the mind is beneficial to the student. Anything that is easy does not discipline.

IN the greatest task of educating the youths of the nation, elementary and preparatory schools labor under extreme difficulties in securing moderates success in disciplining the pupils' minds for concentrated work and independent investigation. The college is thereby handicapped but, in an engineering college, this deficiency should be easily made up if the technical subjects are properly taught, remembering that "Any course of study that disciplines the mind is beneficial to the student. Anything that is easy does not discipline."

The college cannot make engineers; it can only build the foundation on which the graduates will erect the structure of their careers. For a solid foundation, the young man should be thoroughly trained in the fundamental laws of physical sciences and the units of measurements and their equivalent relations. He should also be made familiar and conversant with the use of elementary calculus and analytical geometry as later applied in the study of mechanical, electrical, and other subjects in the curriculum of engineering courses. These should include the physical and mathematical analysis of elements of mechanical structures, thermo-dynamics, flow of water, air and steam, laws of motion of bodies, radiation, transmission and transformation of energy, electrical and magnetic phenomena, et cetera. "It is better to see one thing than to look at a hundred. It is better to conduct a student to the inner chamber of one fact than to take him on a trip seeing greater knowledge." The only fitting time for mastering these fundamentals is during the college years, when the mind is receptive and reposeful, and the aid of the teacher is at hand.

The laboratory work should be planned to give the pupil an insight of the theoretical facts applied to practise. For the same object, it may be beneficial that, in the drafting room, each student or group of graduating students should make to scale detail drawings of a different machine, with accompanying calculations of the important elements affecting its construction. Besides this machine drawing, each group should make a detail project layout of an industrial installation for an assumed definite production or service, like a cotton mill with electric drive, a coal skip hoist, a mine mechanical equipment, an ice plant, a shoe factory, a power plant, a transmission line and substation, et cetera. The benefits accruing to the whole class from these different projects are great, not only for what each student absorbs and makes intimately his own from the close study of the details of his project, but also for what he learns by the interchange of thoughts and ideas with the other students who naturally fall into discussing with each other the features of their respective problems. Such discussions open their minds to widely different engineering problems and broaden their views in correlating the importance of these factors.

In addition to these studies, the pupil should pursue the study of a foreign language, like French, Italian or German, so that he can read and write it fluently, and possibly speak it with facility. I cannot emphasize these advantages too strongly. I do not know of a more broadening, instructive and inspiring education.

My conclusions are that "it is not so much knowing a whole lot as knowing a little and how to use it that counts." The greater the concentration and thoroughness with which the embryo engineers are trained in the fundamentals and their applications, the more self-reliant they will be made for practical life. I wish it to be understood that I do not aim to make engineers theorists, but I wish to instill in them broad and sound theory at the time and place when it can be done most efficiently. My idea is that a broad knowledge of the fundamentals of all physical sciences is the most liberal education with which a future engineer may be endowed.

Discussion

For discussion of this paper see note, page 639.

Better Preparation of Students for Railway Work

With Special Reference to the Telegraph and Telephone Department

BY I. C. FORSHEE
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The more complicated communication systems, their use and importance on railroads, the extension of power transmission lines and electrification of railroads with the resultant effects upon the communication systems require that technical men, who preferably have been given special training that will qualify them to handle such problems, be employed in railroad telegraph and telephone departments. Many problems are in common with the large wire-using commercial companies but others are peculiar to communication systems on railroads.

On account of the great development of the methods and means of electrical communication in railroad work, the extensive and varied uses of such means, and the importance of having the service always available under widely varying conditions, it is becoming increasingly important that electrical engineers adequately trained in communication service be available in the telegraph and telephone departments of the railroads.

On many railroads the telegraph and telephone plant, which is very much larger than is realized by those not intimately informed, compares favorably with some of the large commercial wire-using companies. In such a system, extending as it does over hundreds and in many cases thousands of miles, there are problems that must be solved that are not encountered in the smaller plants. These problems involve an intimate technical knowledge of a specialized nature and many times require careful and extensive investigation and study to obtain the best solution.

While many of the graduates from the technical schools may be well informed in mathematics and fundamentals of physics, chemistry and applied electricity, all of which are essential, yet it is felt that if such institutions and the students contemplating such employment, were more familiar with the railroad communication problems there might be some advantages gained and time saved both by the technical graduates and railroads if there were included in the curricula more practicable applications of abstract theories and principles to concrete cases as met in this department. Many of our problems are common with the large wire-using commercial companies, but others are peculiar to the railroad systems.

It is believed that opportunities for men technically trained and who have specialized on communication work will be greater on the railroads in the future than they have been in the past, as the communication systems are rapidly becoming more complex, the problems of transmission more complicated, troubles from power interference and their solution more involved, and the possible applications of the recent developments more varied and important.

Among the various problems with which the department has to deal might be mentioned:

1. Construction of pole lines carrying open wires or cables or both.
2. Construction of conduit and cable systems.
3. Installation of telegraph and telephone equipment.

4. Telegraph and telephone transmission.
5. Design of circuits.
6. Specifications and tests for construction and maintenance material.
7. Electrolysis of underground structures.
8. Inductive interference.
9. Telegraph and telephone traffic.
10. Accounting and estimating.
11. Preservative treatment of woods and metals.
12. Radio and wire carrier systems.
13. Contracts and patents.
14. Electrical protection.
15. Wire testing, maintenance and service restoration.
16. Engineering research.

There are details associated with each of these items which are peculiar to the application on the railroads. Only general subjects are given and could be amplified appreciably, as will be obvious to one familiar with telegraph and telephone problems.

If more specific information is desired on any of the above subjects it can be obtained from the Secretary of the Telegraph and Telephone Section of the American Railway Association.

Discussion

For discussion of this paper see note, page 639.

Training for Character

BY A. M. DUDLEY
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Some fundamental requirements in the character of a successful engineer as a man and as an engineer are outlined, together with considerations of the school and the instructor to produce and train such a character. Some ideal accomplishments to be attained are pointed out.

THE requirements for character in an engineer are two-fold, first as a man and second as an engineer. The motto which should hang before every worker in every line of work is this; "*First*, be a *man*", with the accent on the first and last words. The fundamental requirements for manhood in engineering are the same as for all professions and may briefly be touched upon as follows; absolute honesty, first with one's self and then with others; sincerity in one's work, remembering that whatever is worth doing is worth doing well; courage to put one's ideas across in the face of influential opposition and courage to accept the results of one's errors and build anew, courage to "keep your head when all about you are losing theirs and blaming it on you"; self control in all things, especially one's temper; self control of the ego, thereby keeping a sense of proportion as to one's real place in the world and preventing selfishness, tactlessness, discourtesy to others and a long train of ills; charity in judging men, recognizing that the heart and real intent are what count and not accidental circumstance; respect for the highest ideal of manhood and man's work in the world, based first, last and all the time on *service*—service to God, man and country.

The special requirements for character as an engineer might be sketched in this way; a fundamental sense of fairness, never letting one's judgment be warped by one's feelings; never distorting physical facts as shown by tests, to fit a theory instead of making the theory fit the facts; generosity in recognizing the good work of others and giving full credit to them and sharing their pleasure in it; recognition at all times of the commercial side of engineering, remembering that "an engineer is one who adapts the forces of nature to the uses of man" and that of two engineers who do the same job equally well from the viewpoint of physical results, he is the greatest who accomplishes it at the least outlay of money or physical resources; character to cooperate to the fullest extent with one's fellow workmen when joined with them to do a job, regardless of temperamental incompatibility or personal likes and dislikes; tenacity of purpose—never to be a "quitter" but to stick to it always and put the job across—*quickly* if possible but *surely* in any event; open mindedness to acknowledge personal error when plainly proved and to start anew without prejudice on the right basis.

To anyone considering this matter there will appear other and perhaps more essential qualities, but these are sufficient to show the necessity for a strong character in an engineer. The next question is how shall this character be trained. The two fundamental requirements are the right institution and the right instructor. No time will be taken here to discuss the relative merits of the exclusively technical school as against the college or university. Men of character graduate from both, and the humblest schools can claim alumni who shine as bright stars in the engineering firmament. But the ideals of the institution must be right. It must regard engineering as one of the learned professions, and as such must not be satisfied with any less degree of scholarly attainment in its engineering faculty than in its divinity or law or medical school. At the same time, since engineering is intensely practical, it should have on its faculty men who have made good themselves in the practise of the engineering profession, who, by their attainments as well as their ability can command doubly the respect of students. Since these specifications for instructors are high, the institution must be prepared and ready to pay a commensurate salary. It should not make the mistake now so regrettably common of employing a high grade man as instructor at a salary below his commercial value and expecting him to carry on a lucrative private practise as a side issue so that he can afford the sacrifice of teaching.

One more thing that the institution should not do if it would preserve the respect necessary to inculcate character in the youth is to carry on commercial research or similar work where the facilities of the school become the source of private profit to outside individuals or to the investigator inside the school. Particularly is this true of institutions supported directly by the state. Wide open publicity as to the result of all investigations and payment made by the client to the school and by the school to the investigator is the only safe course to keep the atmosphere clear and conducive to the best ethical ideals which make for character.

As to the instructor, it is realized his personality and his attitude to his work are the greatest single element in the training of his students in all ways. One of our great men has said that his idea of a university was a log with a student sitting on one end and Mark Hopkins sitting on the other. To be a great success the instructor must be many things which are achieved only after a struggle with human nature. He must be unselfish and self sacrificing. He must be so sure that the building of men is the greatest profession in the world that he will be willing to accept his salary as a teacher and bend his entire energies toward becoming the best possible teacher of engineering. While he has himself practised engineering, he must limit his outside consulting work to an amount necessary to keep his hand in and to serve as texts for his lectures and laboratory work and not use it as a primary means of subsistence. He must be vitally interested in young men and interested in all their phases and problems, capable of advising on human questions of all sorts. He must establish a personal contact that exists beyond the class room and he must use that contact to instill the fundamentals of character while he instills the fundamentals of mathematics and other subjects in the curriculum.

If the school is right and the instructor is right and the student does his part, we shall have an outstanding race of engineers whose word is good as their bond, who bring to their work an enthusiasm that glorifies both the work and the worker, who accept praise and blame with a level head and a steady hand, who take suggestions and ideas from the humblest sources and develop them into real engineering, who give credit where credit is due, who carry their message to Garcia and hang on to the job till it's done, who worry more about the work they are doing than the pay they are getting, who know that a "man's a man for a' that and a' that," and whose personal conception of character blooms into two great requisites for human happiness—good health and the spirit of service.

Discussion

For discussion of this paper see note, page 639.

Some Suggestions Concerning the College Education of an Engineer

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The author considers the first requisite of college training to be a thorough drilling in the fundamentals in physics. A student who is well grounded in the fundamentals is in the best position subsequently to acquire a knowledge of details.

The student's most useful tool to work with is mathematics, but this should be taught to engineers by one who considers it an engineer's tool, and not a source of amusement. All the mathematical results should convey as clear a quantitative meaning to the engineer as numbers do when they represent an amount of money.

A third requisite is the use of mental exercises to develop mental strength. The student should be disciplined by mental exercises in the form of problems which should have some practical significance, so as to show the utility of the mental process, thereby developing interest.

Today is the era of specialists; even electrical engineering, as one subdivision of engineering, is again subdivided into so many branches that a student should either make a choice between them, at least in his last college year, or take a special post-graduate course. Different colleges would do well to specialize on different subjects, especially in their post-graduate courses. The writer has urged that at a time when a student must choose his vocation he has little knowledge of what his choice involves, and it is suggested that the regular college courses should include lectures describing the different vocations, the nature of the work involved in each of them, and the prospects of advancement, salaries, etc. Success in teaching can be measured by the interest that the teaching can develop in the minds of the students.

It is a mistake to keep the able students back to the level of the poorest in the class. The brightest students should be given every possible opportunity to advance.

THE college education of an engineer should be considered to be analogous to the foundations of a building on which a superstructure is subsequently to be erected, rather than to the superstructure. When a foundation is bed rock, it will support any superstructure that may later be decided upon.

The foundations of an engineering education are the fundamentals in physics, that is, the laws of nature concerning matter and energy in their various forms, just as the addition and multiplication tables are the foundations of arithmetic. A profound and thorough drilling in these fundamentals and how to use them should, therefore, be the first and most important requisite; they should be so thoroughly grounded in the mind of the student that they become almost an intuition, involving little effort of mind to deal with them, and an almost instinctive revulsion against their violations. An intuition is well defined as "instinctive knowledge of the relations or consequences of ideas, facts, or actions." As in a building, the foundation is the least conspicuous part in the final product, but it is the part on which the stability of the whole superstructure depends. In a choice between the two, a student well grounded in the fundamentals but with less instruction in the superstructures like specialities, professor's hobbies, details and refinements, will unquestionably become a greater engineer than when the amounts of these two kinds of instruction are reversed. To one who is well grounded in the fundamentals the subsequent acquirement of the knowledge of details and refinements, even if after leaving college, will be a far easier matter than under the reverse conditions.

While these fundamentals are the most useful materials for his work, his most useful tool to work with is mathematics, not pure mathematics but applied mathematics. As a reliable means to arrive at a useful end quickly and directly, it is a most wonderful tool, generally a far better one than arithmetic, but its use as a mere means of entertainment should be left to the mathematicians. It should be taught to engineers by one who considers it an engineer's tool, a utility, and not a mere source of amusement. All numbers and their decimal points obtained mathematically should convey as clear a quantitative meaning to the engineer as they surely do when they represent an amount of money.

Another important factor in the education of an engineer is mental exercise to develop mental strength. When we lift a weight in the gymnasium it is not because there is any useful result in that weight being put on a higher level, but it is to strengthen our muscles. Similarly the mental strength of a student should be developed and disciplined by plenty of mental exercises, say in the form of problems, which should by all means have some practical significance so as to show the utility of the mental process, thereby developing interest; he should be taught to think and reason correctly and not merely have his memory crammed with words and facts as in the teaching of a monkey or parrot. A strong, well trained mind can subsequently absorb details with great ease, with the additional advantages that it can distinguish between the wheat and the chaff, and is not so easily misled. The great mass of engineering facts and data are better preserved in books of reference than in ones brain, which can be made better use of for correct reasoning. Generally a brain is not entirely a vacant space to be filled by college professors, but is rather like a muscle which is to be trained by them to do skilful work.

Knowledge has made such vast strides that in a four years' course it is today physically impossible to teach and mentally impossible to learn, all that it would be of benefit to know. The present is the era of specialists; a Jack of all trades is a master of none; better let a trained financier do the financing, a trained engineer the constructing and a trained salesman the selling. It is imperative, therefore, to make a choice; in general the first choice in an education is that between utility and what might be called polish or ornamental education. Formerly, and in some colleges of today, particularly those for girls, the latter is the main goal. Having chosen utility the next choice is between science and the other learned and useful professions; science and financiering do not always mix well, their standards of morals sometimes differ. In science there are many further subdivisions one of which is engineering, which again is subdivided into branches. Even electrical engineering, as one of these, has so many subdivisions which have little more than the fundamentals in common, that a student ought to make a choice between them, at least in the last year, or take a special post-graduate course. Different colleges would do well to specialize on different subjects, especially in their post-graduate courses, which should then be directed by specialists.

Having decided on any one particular vocational training, the choice of the particular subjects to study should be decided solely and only on the ground of utility. In an electrical engineering course for instance there is so much more to learn than could possibly be crammed into four years, especially when there is an excessive and time robbing indulgence in athletics, that the student is deprived of much useful instruction and training if he has to devote a lot of this valuable time to such things as the dead languages, bible history, literature, etc. The proper use of the English language should have been taught in the preparatory schools.

The subsequent failures of college trained men have frequently been due to a mistake in the selection of their course in college. Other conditions being equal, the best choice is unquestionably the subject in which he is most interested. But in most cases at the time he has to make the choice he has no proper knowledge of what a particular career involves; the fact that as a little boy he enjoyed playing with toy electric railways does not, as some fond parents think, mean that he will make a good electric railway engineer. The writer has, therefore, often urged that at the time when the student must make a choice, a part of the regular course should be a few lectures describing what the various vocations involve, what subjects he will have to agree to study in each one, what the nature of the work will be and what the prospects are of employment, advancement and salaries. Such lectures would unquestionably greatly reduce the deplorable number of misfits and the great loss of time in later changing from one course to another.

The province of a physicist is to discover and formulate the laws of nature regarding matter and energy while the province of the engineer is then to apply these laws for the benefit of mankind. Another definition of an engineer in popular terms is that he is one who can show how a thing can be done for one dollar that any fool can do for two dollars; a complementary definition of an administrator, or organizer, at least of some of them, then is that he is one who can get two dollars for something worth only one. In recent times, so many engineers have abandoned the true profession of engineering, that of designers and constructors, and have become administrators, organizers, financiers, or salesmen, for which positions their engineering training has undoubtedly helped them greatly, that these and many others, like the handling of labor, have recently often been included under engineering, a noble name to conjure with. Larger salaries and less interest in engineering, are generally the incentives for the change; some adminstrators can vote themselves their own salaries. But whether this modern use of the term engineering is desirable or not, it is true that an engineering training is of great value in such positions, and that, therefore, students should be told about these vocational possibilities and if they choose them they should be given a somewhat different course omitting certain studies and substituting others.

In the writer's opinion, success in teaching can be properly measured by the interest that the teacher can develop in the mind of the student. There are, of course, some very necessary studies that are without any interest, and, therefore, pure drudgery, like learning the multiplication tables, rules, terms, relations, formulas, etc, but aside from such cases of mere memorizing of some necessities, when a teacher cannot awaken the student's interest either the student is hopeless and should leave college, or else that teacher has not mastered the real art of teaching. Often have students told the writer how greatly they were interested in a certain subject, adding the significant clause that they liked that particular teacher, as he made it so clear; in the reverse case it may be the fault of either or both.

A serious error in many colleges, which might even be called an educational crime, is to keep the bright and able students back to the level of the poorest in a class. It should be the duty of every teacher to give the brighter students every possible opportunity to advance. The deficient ones should either be helped to catch up or made to repeat the previous year's work.

Students naturally take a delight in pointing out errors in what their teacher has taught them; finding such errors also tends to shake their confidence in other things he taught them, which is fatal; they also lose interest and respect when they find there is a simple, easily understood way of explaining something which they had been taught in a complicated, confusing way which was difficult to understand and hard to retain. It is therefore of the greatest importance for the teachers to be absolutely sure of the correctness of what they teach and to keep abreast with the times in their interpretations and explanations. It is, for instance, an intellectual crime, which might do much harm, to teach that a law is universal after it has been shown that it is not. The writer has been surprised to see the strong opposition of some teachers to modify their teachings of a year before in accordance with developments during that time.

What constitutes success in a career is variously defined and is a matter of opinion. Some measure it by the ratio of the money received to the time and effort spent, that is, the present labor union idea of doing the least work for the most money. According to that scale one who loots a bank is at the head of the list of the successful; there is a wide difference of opinion as to what is and what is not honorable; when the looting is done by a teller, he is a criminal, but when done by the president he is an expert financier. Others think that success is measured by the kind of service rendered or by doing something that is of some lasting benefit to mankind and to the world, such as the products of the researches of scientists, the discovery or development or invention of something useful, or erecting great and useful structures. Students have their choice, some look only for the dollar, others for something higher; the choice of their college course depends somewhat on this; many persons have made much money without having had a college course, but today the so-called self-made engineer who has not had a higher education and has not made up for it later, is hopelessly handicapped as an engineer in competition with those who have.

The engineer deals with the laws of nature, which govern him; nature is mercilessly strict in insisting on their enforcement to the letter; such a training therefor, tends to develop a respect for laws, an instinctive effort to do only what is right and to abhor what is wrong. He cannot cover up his faults or ignorance as doctors, lawyers, financiers and ministers can, and he must therefore be better trained. An engineering training is therefore also ethical in its effect.

Discussion

(Owing to the large volume of discussions on the educational papers presented at the Annual and the Pacific Coast Conventions it has been found advisable to omit them from this volume of TRANSACTIONS. They have, however, been published in full in pamphlet form and copies of the same may be procured by anyone interested on request to Institute Headquarters.)

Baltimore Oil Circuit Breaker Tests

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and

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***Review of the Subject.**—In view of the tremendous growth of electric power systems it has been realized for sometime by many of the larger operating companies that many of the old circuit breakers were not adequate for the increased duty. There seemed also to be considerable uncertainty as to the actual ratings of many of the more modern types. It was realized that this condition was largely due to the fact that the manufacturer was handicapped in making tests due to lack of power. These circumstances led the Consolidated Gas, Electric Light and Power Company of Baltimore and the Pennsylvania Water and Power Co. to make a series of oil switch tests on their interconnected 13,200-volt, 25-cycle power system, cooperating with the Westinghouse Electric and Manufacturing Company and the General Electric Company.*

The largest generating capacity used on these tests was 170,000 kw. Currents obtained vary from 750 to 23,700 ruptured r. m. s. arc amperes.

All of the tests were made by throwing three-phase metallic short circuits directly on the system which the breaker under test was called upon to clear immediately. Proper protection of the system was provided in case of failure of test breaker.

Three oscillographs were utilized to record the sequence of events. A total of about 200 short circuits was made directly on the Baltimore system without any breakdown whatever of the major equipment of the two operating companies, and in practically all cases without causing more than a momentary voltage disturbance to the system.

The results as described in the papers submitted by Messrs. Hilliard and MacNeill indicate that it is possible with proper design to build oil circuit breakers which can be relied upon to satisfactorily interrupt large currents on high-capacity systems many times in succession without damage to the breakers, without oil throw, and without change of oil or adjustments.

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THE tremendous growth of electric power systems with corresponding increase in size and number of generators, feeders, transformers and other station apparatus, has thrown an ever increasing duty on the switching equipment. Likewise, the modern tendency to secure higher efficiency, economy and flexibility by interconnection of older systems and running all the generating stations in parallel, has still further augmented the burden of oil circuit breakers. The high degree of reliability and continuity of service generally expected, also necessitates high standards of oil circuit breaker performance. That not all of the oil breakers at present in service were able to meet these new demands, has been realized for some time by many of the larger operating companies. Older breakers were proving themselves inadequate for heavy duty, while breakers of later design were not entirely satisfactory. Some breakers failed to clear short circuits, were badly injured or completely wrecked, throwing oil and parts around by explosive action, with consequent danger to other apparatus and station attendants. Occasionally even serious oil fires would result from the failure of a breaker forcing the operators to abandon the station for a time. Even when breakers cleared they were frequently damaged, requiring the breakers to be carefully gone over, repaired, and adjusted and refilled with oil, before being put back in service. That is, many breakers could not be relied upon to handle more than one heavy short circuit without repairs or adjustments of some kind, making them virtually "one short" breakers. This limitation of the number of times a breaker could satisfactorily open heavy currents was indeed a serious drawback.

There has also been considerable uncertainty as to the individual performance and rating of the various sizes and types of oil circuit breakers. This placed the selection of the proper type and size of breakers for new services, and design of new stations on a very uncertain basis, with little exact information upon which to base designs and selection of sizes. With the large investments involved, this lack of exact knowledge made a most undesirable condition.

That this situation has existed for some time has largely been due to the fact that the manufacturers were handicapped in making tests to obtain the desired information, by the lack of sufficient power which would approximate conditions on actual power systems. Tests have been made before, but these were generally few in number or involved relatively small capacity, as most operating companies were averse to risking their equipment in any extended set of tests. Still this was necessary as a very important consideration is that small generator capacity not only limits the short circuit currents to low values, but causes the voltage to fall off so rapidly that a breaker opens a very low voltage, thus destroying the value of tests made under these conditions.

These circumstances and conditions caused the Consolidated Gas Electric Light and Power Company of Baltimore and the Pennsylvania Water and Power Company to make an elaborate set of oil circuit

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breaker tests on their interconnected 13,200-volt, 25-cycle power system, in cooperation with the Westinghouse Electric and Manufacturing Company and the General Electric Company, which furnished the switches tested. Generator, transmission line and cable capacity were furnished equalling or even exceeding normal operating conditions. The fact is the currents obtained in the tests exceeded those usually met with in short circuits on this system. All the tests were made by throwing "dead" metallic short circuits on the entire connected system, which the breaker under test was called upon to open.

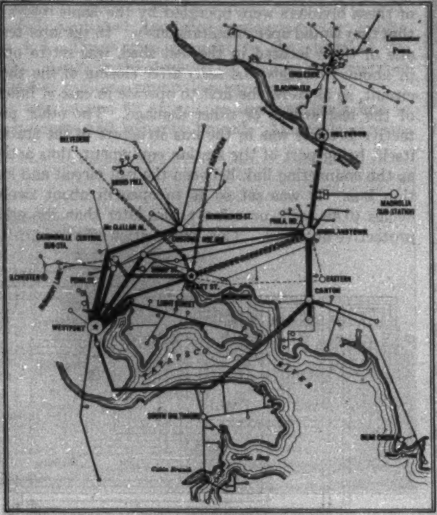


FIG. 1—SYSTEM DIAGRAM

Baltimore Gas, Electric Light and Power and Pennsylvania Water and Power Companies.

The Canton substation in Baltimore was selected as the best location for these tests for several reasons:

It is situated about seven miles from Westport, the main steam generating station of the Consolidated Company, and about forty-one miles from the hydraulic power plant at Holtwood of the Pennsylvania Water and Power Co. and current can thus readily be supplied from both of these generating stations over a large number of cables and transmission lines, as shown in Fig. 1. The current in this way becomes well distributed on the generators, transformers and feeders, without excessive overloading of any individual units.

Some other locations such as Westport might have given higher initial currents, but these would have caused the voltage to fall off more rapidly due to greater demagnetizing action, thereby making it questionable whether the breakers actually would be subjected to a more severe duty than at Canton. Actual test results showed the great effect of sustained voltage. The voltage at Canton, *i. e.*, the re-established voltage, appearing right after the short circuit was cleared was never less than 77 per cent normal voltage, even after the heaviest short circuits obtained, and on lighter short circuits was practically normal.

Furthermore available space at Canton permitted of convenient arrangement of sheds sheltering oil breakers under test outside of the station. These also could be located so as to be of little or no hazard to either the company's or other people's property in case of failure of the switch. It was, also possible for observers carefully to watch the tests at a safe distance with little danger to themselves.

CAPACITY OF SYSTEM

The main steam generating station of the Consolidated Gas Electric Light and Power Company, which is located at Westport, has a generating capacity of 127,500 kw. in steam driven turbo-generators, of which 87,500 kw. was usually available for tests. The generating station of the Pennsylvania Water and Power Co., at Holtwood, Pa., has a generating capacity of 83,500 kw. in water-driven units. There is also one 20,000-kw. steam-driven unit at the Pratt St. Station in Baltimore. These three generating stations are interconnected through a number of substations, giving the system a combined generating capacity of 231,000 kw. The maximum generating capacity used in these tests was 170,000 kw. Canton substation is directly connected with the Westport steam station by four 26,000-volt submarine cables, banks of transformers being provided at either end, and is also tied to the city network by eight 13,200-volt cables through the Pennsylvania Water and Power Co. Highlandtown substation.

As breakers of various rupturing capacities were tested, it was necessary to get various values of short-circuit current. Also, some tests were made by starting in at low values of current.

To obtain these short-circuit currents of different magnitudes the number of generating units was varied to some extent, but the main variation in current was obtained by changing the cable connection between the generating stations and the test bus at Canton substation so that even in the case of the minimum current used a very large capacity was behind the short circuit. From the constants of the system the short-circuit current of a large number of possible combinations of generators, transformers, and transmission arrangements were thus calculated and these figures used as guides for our set-ups in the tests. A typical arrangement used is shown on Fig. 2. It is perhaps remarkable to note that these calculations came within 5 to 15 per cent of the currents actually obtained in the tests at the time of rupture.

CURRENTS OBTAINED

All the tests were made at 13,200 volts, 25 cycles. Short circuits ranging from 950 to 30,800 initial r. m. s. amperes and from 750 to 23,700 ruptured r. m. s. amperes were obtained. The water-power station being far removed from the test bus supplied about 30 per cent of the initial short-circuit current, 70 per cent being supplied either by Westport alone or by Westport and Pratt St. stations. The maximum instantaneous loads on any of the generators did not exceed five times the normal load. Under the heavy short circuits, some cables (4/0) carried from 2000 to 2500 amperes.

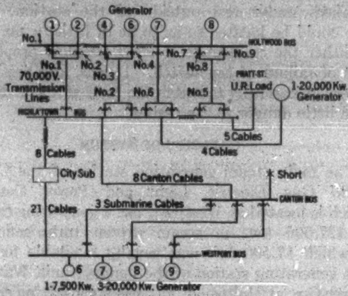


FIG. 2—TYPICAL TEST ARRANGEMENT OF SYSTEM

Calculated short-circuit current:
Initial = 29,400 r. m. s. amperes at 42.2 per cent power factor.
After 5 cycles = 24,850 amperes at 39.3 per cent power factor.

Most of the short circuits were made across all three phases and ground. A few were across two phases and ground, and several on one phase and ground only. After finding that two-phase and single-phase short circuits produced severe vibration of turbo-generators, they were subsequently avoided. In this connection it should be pointed out that in the Baltimore system the neutral of all generators and transformers is "dead" grounded without any resistance, so that in each three-phase test it was necessary for each individual phase of the oil circuit breaker to clear its own part of the short circuit without any help from the other phases, as might have been the case in any ungrounded or partially grounded system.

TEST BREAKER ARRANGEMENT

The general method of testing was to throw a dead short circuit on the breaker under test, which was set to open instantaneously. Two other oil circuit breakers were in series with the test breaker serving as protective breakers in case of failure of the test breaker, being set for later opening. A separate switch was used to act as closing-in breaker exclusively. There were thus four breakers in all used in the test circuit, which was connected to the system set up to give the desired currents.

Fig. 3 shows the arrangement of the four breakers in detail. The breaker under test was next to the short-circuit connection, which provided a metallic short circuit between all three phases and ground. It was arranged to trip automatically by means of a plunger type relay with "instantaneous" time setting, the only delay being that due to the inherent characteristics of the mechanism and relay. This varied from three to nine cycles (0.12-0.36 sec.) The closing in breaker was non-automatic and was closed by means of a switch under the control of the oscillograph operator. The protective breakers were operated by Westinghouse type CO time element relays. In the earlier tests both of these breakers were operated by the same relays so that they would open simultaneously. In the later tests one of them located in the test shed, was set to open in about 10 cycles (0.4 sec.) after closing of the short circuit, so as to be the first to operate in case of failure of the test switch or other damage. The other protective breaker was in the bus structure of the station itself, being part of the station equipment, thus acting as the connecting link between the test circuit and station bus. It was set so as to open in about twelve cycles (0.48 sec.), or a few cycles later than the other protective breakers. This combination afforded protection not only against failure of test breaker, but against failure of closing-in breaker, or one protective breaker, also breakdown or short circuit of leads. Some of these different troubles were experienced during the tests. Both of these schemes of protection proved to be absolutely adequate throughout the many tests, as in no case did the protective breakers fail to clear the test equipment from the bus in the station.

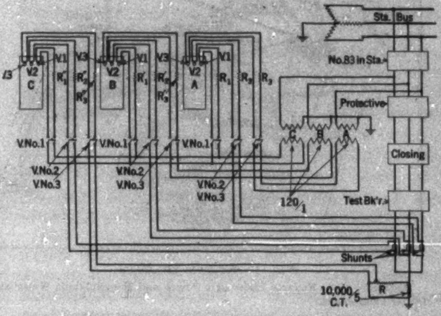


FIG. 3—DIAGRAM OF TEST BREAKER ARRANGEMENT AND CONNECTION OF OSCILLOGRAPH ELEMENTS

TEST SHEDS

The test breakers were placed in temporary sheds about ten feet from the station. Three breakers were originally placed in one shed, but as injury to the test breaker in early tests was communicated to the others a second shed was built and the test breaker placed in it. The general arrangement is shown in Fig. 4. Doors were put in the ends of each shack, providing accessibility and ease of observation.

Sheds were built of wooden framework, covered on the inside with galvanized corrugated iron as a protection against the weather and fires. The floor of the first shed was dirt at first, but this was replaced later by a wooden floor to which the switches could be bolted to keep them from rocking. The floor of the second shed only was made of concrete.

LEADS

Leads to sheds from the station consisted of lead-covered varnished cambric single-conductor cables, size 4/0. These were brought to the sheds in tile ducts. Leads in the sheds to switches were flameproof varnished-cambric, rubber-insulated wire.

It was learned by experience that the leads had to be carefully and securely braced. Magnetic stresses produced by heavy short-circuit currents caused a great tendency of leads to shift and whip, sometimes resulting in breakdowns. It was also found that very careful attention had to be given to soldered joints and connections, as repeated heavy currents by heating and pulling action caused defective joints to open up with consequent arcs, which sometimes spoiled the tests and often damaged other parts. Not only did this pertain to the connections in the test sheds but it was also of special importance in the leads in the station connected with the test, in order to prevent trouble being communicated to the rest of the station, as occurred in one case with considerable damage. Therefore, in the station proper, all buses were carefully gone over and specially braced. Disconnects were also given special attention, in fact, some of these were eliminated in any cables which carried excessive currents.

FIG. 4—TEST SHEDS

FIG. 5—OSCILLOGRAPHS AND CONTROL APPARATUS FOR TESTS

MEASUREMENT OF TIME, CURRENTS AND VOLTAGE

Three oscillographs containing three elements each were used, thus making a total of nine elements, and three films. Each of these generally recorded the current in one phase and corresponding voltage to ground. In order to provide a common timing curve two of the films in addition to their own voltage (to ground) also recorded the voltage corresponding to the third phase. The third film in addition to its phase current and voltage also recorded the ground current.

Potential transformers were connected from each phase to ground at a point between the two protective breakers, thus providing a measure of voltage across each phase of the test breaker, showing in succession

FIG. 6—LAMINATED SHUNTS, 10,000-AMPERE, PLACED IN A TRIANGULAR FRAME

full voltage before the short circuit, zero voltage and arcing voltage during the short circuit, and the reestablished voltage after the short circuit was cleared, thus indicating the action of the various breakers. Fig. 5 shows a typical arrangement of these oscillographs.

In some cases it was desired to accentuate the scale of the arcing voltage, in which case one potential transformer was connected directly across one phase of the switch, and oscillograph resistances adjusted to give heavy deflection even at low voltage. This put excessive currents in the vibrator circuits, so a gold-leaf fuse was inserted in this circuit, which blew at high voltage which occurred due to complete restoration of voltage across breaker contacts on opening up. This scheme could not well have been used on all phases as it cut out other useful and necessary information obtained with the regular connection. A study of the voltage at the arc was also obtained by making photographic enlargements of parts of the oscillograms of voltage waves taken in the regular way.

For current measurements, slip-over type current transformers were used by one manufacturer. These were put on the line between the two protective breakers. The other company used shunts to measure current. As the use of these brought the oscillograph elements to the same potential as the shunts, these shunts were put in the leads at the short-circuited and grounded end of the test breaker. To further insure keeping this grounded end at ground potential and prevent the burning open of this ground, the size of this ground wire was doubled, two 4/0 wires being used. The scheme worked out generally satisfactorily, as no markedly bad effects were experienced, although shunt leads were charred in the conduit several times.

In the first tests the shunts were located in the same plane. In later tests they were located in the corners of a triangular wooden frame with axes parallel to incoming current leads, see Fig. 6. Care was taken to bring the instrument leads out from the center line of the shunts. These instrument leads consisted of twisted pairs; an important consideration, as failure to twist these leads in early tests had caused errors due to inductance effects. The latest arrangements of leads and shunts were made so as to reduce the effects of inductance to a minimum; in fact results indicated these to be practically negligible.

Current transformers and shunts each have their particular advantages as well as faults. There is some question as to how accurately current transformers record transient phenomena. Furthermore the partial saturation of the iron produced by heavy overloads during short circuit introduces other errors. However, current transformers can carry surprisingly heavy overloads with a fair degree of accuracy. It should be remembered that the oscillograph itself has but limited accuracy. On the other hand shunts record accurately transient phenomena. They are, however, subject to inductive effects, which can introduce considerable error. The uneven distribution of current in these may also introduce other, though probably slight errors. The ever present danger of putting line voltage on the oscillograph is of course a serious objection.

OSCILLOGRAPH LAYOUT

In the Westinghouse tests three oscillographs as developed by J. W. Legg were used. The special features of these oscillographs are described in detail in the July, 1920, JOURNAL of the A. I. E. E. and will not be dwelt on here, except to point out such outstanding features as the use of incandescent lamps instead of arc lamps as a source of light, and the automatic arrangements which make it possible to secure the start of the short circuit at the beginning of the film, thereby making it possible to use satisfactorily short films only 12 in. long. In the G. E. tests, three standard G. E. oscillographs were used, all driven from the same jack shaft. 24-in. films were used, and the general method adopted was to start the oscillograph a moment before the short circuit was applied, and then close in the oil switch which applied the short circuit to the system independent of the oscillograph, both the switches controlling the oscillograph and the closing-in breaker, however, being under the immediate control of the oscillograph operator.

FIG. 7—TYPICAL OSCILLOGRAM

ANALYSIS OF OSCILLOGRAMS

Fig. 7 shows a typical oscillogram. The bottom curve represents the current in *A* phase and the top curve the corresponding voltage measured to ground. The middle curve represents the above mentioned reference voltage (*C* phase). It will be noticed that *A*-phase voltage becomes zero the moment the short circuit current appears, but later on reappears as a typical "arcing voltage", with the well known flat arc characteristic, corresponding to the instant the arcing contacts separate. After a little over one-half cycle of arcing the current in this case is ruptured and practically normal phase voltage reappears. By far the larger percentage of short circuits seem to break the arc at the zero point of the current wave corresponding to the time at which the magnetically stored energy of the system is a minimum. Occasionally exceptions are found to this rule. Oscillogram Fig. 8 shows such a case where the arc broke about 1/10 cycle after passing through its zero point. The method adopted in determining the r. m. s. current value from the oscillograms was the one described in the A. I. E. E. paper of February 19, 1918, by Messrs. Hewlett, Mahoney and Burnham on the rating and selection of oil circuit breakers. Illustration Fig. 9 shows the application of this method in detail in one particular case. As indicated, the current is divided into an a-c. and a d-c. component whenever unsymmetrical and the true r. m. s. value of current at any moment is obtained by combining the effective a-c. component ($I_{a.c.}$) and the d-c. component ($I_{d.c.}$) in the usual way, *i. e.*,

$$I_{r.m.s.} = \sqrt{I^2_{a.c.} + I^2_{d.c.}}$$

To determine the true r. m. s. value which the breaker interrupted, the component parts are taken from the films at the moment the arc voltage first appeared, *i. e.*, at the instant the arcing tips parted. At this time in most cases, however, the d-c. component of the current wave was usually negligible. To determine the maximum r. m. s. obtained on the short circuit, the components parts were taken at the peak of either of the first two half waves, depending on which was the largest. Unless specifically stated otherwise, all the current values quoted in this and subsequent papers refer however to the actually ruptured arc amperes and not to the initial amperes.

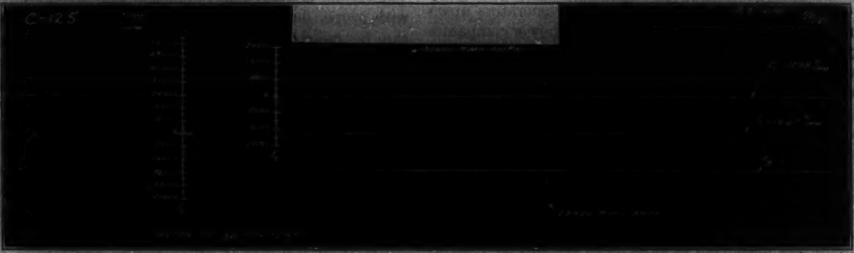


FIG. 8—OSCILLOGRAM SHOWING CURRENT RUPTURED PAST THE ZERO POINT

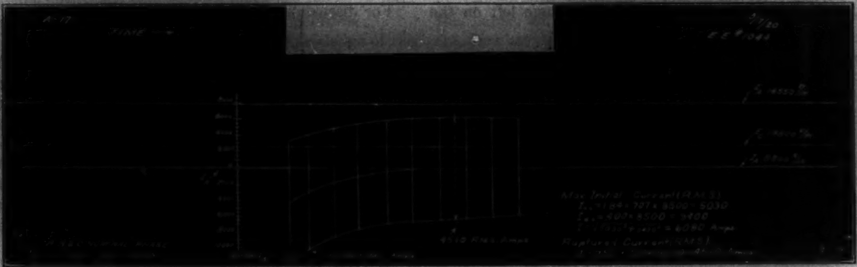


FIG. 9—OSCILLOGRAM SHOWING METHOD USED IN CALCULATING THE R. M. S. VALUES

EFFECT ON THE SYSTEM

It may be interesting to note that it has been possible to make a total of about 200 short circuits directly on the Baltimore system at Canton, many of which involve the largest short circuit obtainable at this place without any breakdown whatever of the major equipment of the two operating companies, and with no more than two serious disturbances resulting to the system, one being due to the opening of a disconnector in the station, and the other being caused by the burning open of one of the leads in the station at its terminal. All of the tests naturally meant momentary voltage disturbances to the system, and for this reason most of the tests were made after midnight or on Sunday morning when such momentary disturbances could best be tolerated. In some of the later tests the load of a number of the more important customers was also carried on separate generators apart from the tests. In no case did the two power companies generators fall out of step, and in only a few cases was any of the customers' synchronous load lost momentarily. The most sensitive equipment on the system seemed to be the rectifiers used for street lighting which frequently would drop out, but as these could always be re-started immediately, this was not considered of serious consequence. The chief reason for the fact that it was possible to make so many short circuits with so little serious interference with the system lies undoubtedly in the short duration the short circuit was permitted to hang on to the system, usually not more than ¼ second and never more than ½ second. Additional reasons may be the fact that short circuits were not made directly at the generating stations so that there would always be some voltage left on the generators to maintain synchronism, and the fact that the system in question is equipped with a carefully designed and adjusted selective relay system.

CONCLUSIONS

In the papers presented by Messrs. Hilliard and MacNeill the individual performance of a number of breakers are described in detail and will therefore not be dwelt on here. A study of these papers will show that the tests have resulted in marked improvements in the design and performance of oil circuit breakers for moderate voltage and high interrupting capacity. The results unquestionably indicate that it is possible, with proper design, to build oil circuit breakers which can be relied upon to satisfactorily interrupt large currents on high-capacity systems many times in succession without damage to the breaker, without any oil throw and without change of oil or adjustments.

The tests have also proved that it is possible to conduct a series of tests directly on a modern system without damage to equipment and without serious interference to its normal operation. It is hoped that this fact will encourage other operating companies to cooperate with the manufacturers in further improvements of oil switches of other designs and ratings to the benefit of the whole industry.

Discussion

For discussion of this paper see page 662.

Tests on General Electric Oil Circuit Breakers at Baltimore

BY J. D. HILLIARD

General Electric Company, Schenectady, N. Y.

DURING the year 1920 an invitation was received by the General Electric Company from the Consolidated Gas Electric Light and Power Company of Baltimore, Maryland and the Pennsylvania Water and Power Company to submit oil circuit breakers for test on their system in Baltimore. The object of the test was to develop a breaker which would satisfactorily handle a short circuit on the 13,200-volt, 25-cycle system as it then existed, and show an apparent factor of safety at that load (20,000 to 25,000 r. m. s. amperes) which would be fairly conclusive to them that the breaker would also handle a short circuit on the system of at least 40,000 amperes. r. m. s. when the generating capacity had been increased by a proposed new generating station.

The tests proposed offered greater advantage than any heretofore made because the power available for testing at this voltage was much greater than any previously employed, because the breakers were to interrupt short circuits at the working busbars of the system, instead of utilizing an isolated bus section as had heretofore usually been the case at tests, and because the tests were to be made by the two companies above mentioned who were to make the report of tests and draw their own conclusions as to operations.

It is obvious that without an exact knowledge of the facts and conditions governing the tests the engineers of power companies might draw wrong conclusions, and if these conclusions were applied to their own system they might be unduly concerned with their equipment, which as a matter of fact might be perfectly safe under their conditions of operation. For that reason it was stipulated that no report of operations were to be made public without the consent of all parties concerned.

It is important to emphasize that the tests on General Electric apparatus herein reported are not to be taken as *applying universally* to all 13,200-volt, 25-cycle *systems and circuit connections* but are conclusive *only upon this particular system under the particular connections used during the tests* with the *special* circuit breakers tested. Conclusions drawn from these tests and applied to systems where different conditions exist and where standard breakers are installed may lead to unfortunate results. It is believed that the wisdom of the company's conservative policy in the rating of current-interrupting apparatus is conclusively proved by these tests.

After it had been decided that the company would accept the invitation and submit breakers for test, consideration was given to the selection of the type of breaker best suited to meet the severe conditions. The Type *F H* breaker was decided upon for the following reasons: Its satisfactory operation in the past; the small quantity of oil these breakers contain relative to their interrupting capacity, with a corresponding small fire risk; the great strength of the oil-vessel; the ease of making inspections and contact repairs on the spot, or of substituting spare vessels and inspecting those removed at leisure; the impossibility of the arc going to ground by burning through the insulating lining of the oil tank; the fact that since each arc is drawn in its own tank there is no possibility of the arcs whipping together causing a sustained short circuit; the possibility of greatly increasing the interrupting capacity of this type of breaker in a cell of the standard floor space and the fact that so many stations were already equipped with this type of breaker.

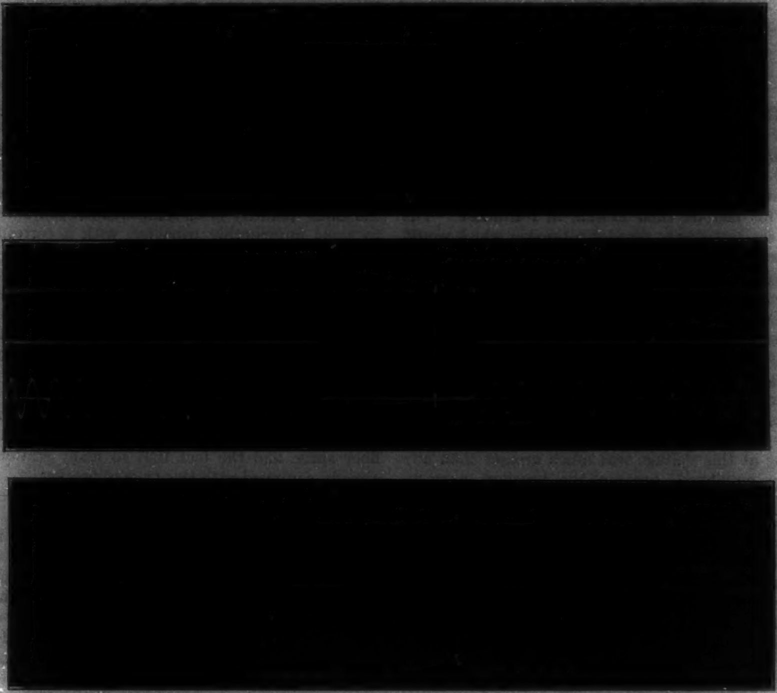
After some preliminary testing the Consolidated Gas, Light and Power Company changes the specifications as to the number of short circuits the breaker was to open, from two to five successive short circuits at two-minute intervals. The tests as reported in this paper, which were to determine the suitability of the breaker to handle five successive short circuits with all the power the operating companies could deliver were not begun until after the changes indicated as a result of the preliminary tests had been made. The remodeled breakers consisted of one *F H*-3 *Y*, one *F H*-6 *Y* and one *F H*-9 *Y*, and a single pole of the experimental *F H D*-17 *Y* the so-called dead pot *F H* breaker. The remodeled type *F H Y* breakers differed from the standard type *F H* breakers in having heavier tops, contact rods, bolts and bolting members, also heavier internal baffle construction, and an external separating chamber of insulating material, leading from the top of each oil tank, through which the gas is ejected and in which chamber any atomized oil vapor is retained by the condensing material contained in the tube, and returned to the oil tank. Various lengths of oil tanks were also provided and tested as well as various separating arrangements in order to determine the one most satisfactory to prevent oil throw.

This external separator was so designed that it could be placed on the present type *F H* breaker in the standard size cells after suitable modifications have been made to the breaker elements.

THE TESTS

Type *F H*-3 *Y* breaker interrupted an average current of 20,600 r. m. s. amperes once without oil throw.

Presented at the A. I. E. E. Annual Convention, Niagara Falls, Ontario, June 26-30, 1922.



Oscillograms Nos. 136-*A*-*B*-*C*

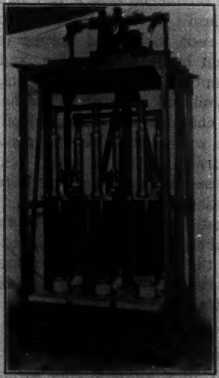


Fig. 1—Front View of Test Breaker Frame With Type *F H*-3 *Y* Tanks in Place

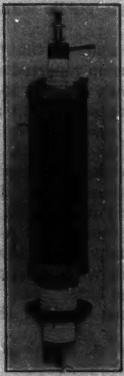


Fig. 2—Type *F H*-3 *Y* Tank Completely Assembled

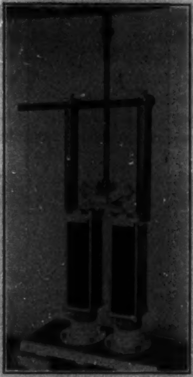
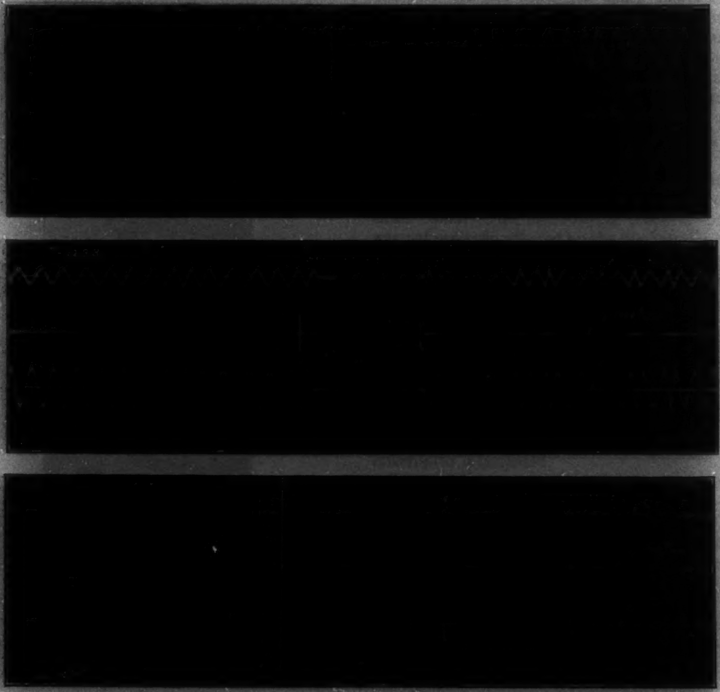


Fig. 3—Type *F H*-3 *Y* Single-Pole Element—15,000-Volt Breaker

The same breaker interrupted an average current a second time at 20,200 r. m. s. amperes at the arc without oil throw. At this second shot a defective lever arm on the mechanism broke and the breaker was not tested further. The generator capacity connected was 147,000 kw., oscillograms 136 *A*, *B*, *C* show the circuit phenomena during the interruption. Fig. 1 and Fig. 2 show the triple-pole breaker and a single-pole element as tested, and Fig. 3 shows a standard single-pole element of the breaker as furnished for standard production orders.

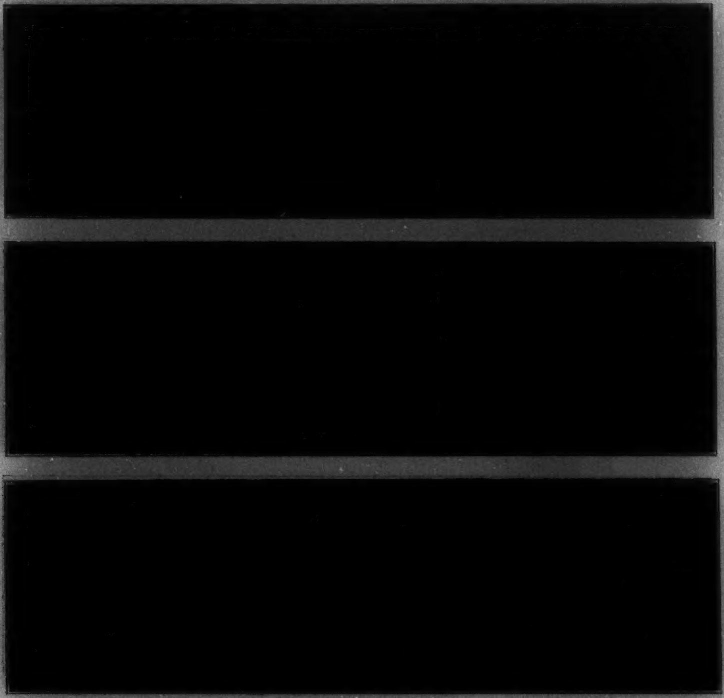
The type *F H*-6 *Y* breaker interrupted five successive short circuits averaging 20,200 r. m. s. arc amperes. A few drops of oil was the extent of the oil throw in any of the tests. Some smoke was emitted from the separating pipes but no distress was shown by the breaker and it was evident that the load interrupted was much below its interrupting capacity. The generator capacity connected was 147,500 kw. oscillograms 129, *A*, *B*, *C* show the circuit phenomena during



Oscillograms Nos. 129-*A*-*B*-*C*

Fig. 4—Type *F H*-6 *Y* Oil Circuit Breaker Completely Assembled

Fig. 5—Type *F H*-6 *Y* Oil Tank Assembled with Bushings and Reenforcing Rods



Oscillograms Nos. 140-*A*-*B*-*C*

the interruption. Fig. 4 and Fig. 5 show the triple-pole breaker and a single pole element as tested.

The type *F H*-9 *Y* breaker interrupted five successive short circuits with an average current of 19,160 r. m. s. arc amperes. The oil throw was limited to a few drops during any test except from a leaky gasket on phase *C*. The breaker evidently has a large reserve interrupting capacity above any load which could be thrown on it during the tests. The generator capacity connected was 147,500 kw. oscillograms 140 *A*, *B*, *C* show the circuit phenomena during the interruption.

Oscillogram No. 147

The type *F H D*-17 *Y* breaker—single pole element—interrupted five successive short circuits averaging 17,670 r. m. s. arc amperes. During this series of tests the oil throw was very small and it was evident that the interrupting capacity of the breaker was much greater than the available load which could be thrown upon it from the system. The generator capacity connected was 147,500 kw. Oscillogram 147 shows the phase phenomena during the test. Fig. 6 shows the single-pole element as tested. This test of the type *F H D*-17 *Y* breaker was a single-pole test; the other two poles at the time of the test were the type *F H*-9 *Y* breaker elements.

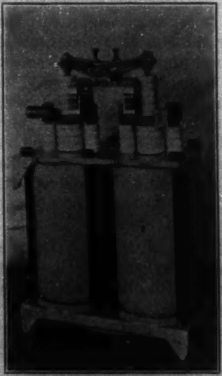


Fig. 6—Type *F H D*-17 *Y* Oil Circuit Breaker, Single-Pole Unit, 15,000 Volts, 1200 Amperes

This type *F H D*-17 *Y* breaker was not tested with its regular operating mechanism but with the standard type *F H*-9 *Y* mechanism, the single-pole element therefore did not show the exact characteristics it would have shown if its own operating mechanism had been used. The burning of the contacts and contact rods for the five short circuits was small on all of the breakers tested and was substantially the same for all breakers (about 1/4 inch was burned from the end of each contact rod.) This is what would be expected because the size of all contact rods was the same.

The quantity of oil lost was negligible and was as to be expected less in the larger oil tanks than in the small tanks. The interrupting property of the oil was not seriously affected by the five interruptions and it is evident that oil deterioration is not the factor which will determine the number of interruptions which can be made by any of these breakers.

The interrupting capacity of any of the *F H Y* type breakers can be increased to almost any desired current by making a small modification of the oil vessels, but the number of interruptions which can be safely made at any current and voltage will, of course, decrease with the increase of current, unless the arcing contacts are increased in size at the same time the current to be interrupted is increased.

The Baltimore tests, as well as other tests where large currents have been interrupted, have demonstrated the necessity of maintaining the arcing contacts in good condition, because the safety of the main contacts are determined by the condition of the arcing contacts. These remarks, apply to oil circuit breakers of any type.

The breaker may be designed for instance to stand four interruptions, but if it has handled two interruptions without examination there are but two left at the guaranteed rating, and at the next case of trouble the breaker may have to open so many times that the main brushes will be seriously burned before the trouble is remedied, and if so, the carrying capacity of the breaker will be seriously affected. The necessity of keeping the arcing contacts in first class condition at all times on breakers of any type interrupting large currents cannot be overemphasized, the continuous operation of the system and the safety of the breaker both require it.

In the recording by the oscillograph of the currents interrupted, shunts were used instead of current transformers, as the company's engineers feel that they more correctly record the transient phenomena.

In taking the records, two foot films were used as their use enabled us to spread out the wave and thus secure a better record and at the same time assured a record of any delayed phenomena, such as the reestablishment of the arc, should it occur, which could not be had with the short film. With the long film it is also possible to obtain a good record without adjustment of the drive of the oscillograph on breakers having widely different speed characteristics.

CONCLUSIONS

The test proved that the *F H* type of breakers could be constructed to interrupt the heaviest short circuit on a large power system within its voltage rating and without oil throw; that the present line of type *F H* breakers could be changed so as to be free from oil throw at their present rating.

We wish to here express our appreciation of the many favors shown us by the power companies during the tests. The manufacturing and operating companies both are deeply indebted to them for supplying the facilities and labor with which to make the tests which made possible the realizing of results not otherwise obtainable at that time. It took a great deal of courage to throw repeated short circuits on the combined systems and the results showed that their belief in their engineering practise and substantial construction were merited, as not a single serious accident to personnel or apparatus occurred during the series of tests.

Discussion

For discussion of this paper see page 662.

Tests on Westinghouse Oil Circuit Breakers at Baltimore

BY J. B. MacNEILL
Associate, A. I. E. E.
Westinghouse Electric and Manufacturing Company, E. Pittsburgh, Pa.

This paper deals with short-circuit tests made recently at Baltimore on dead tank oil circuit breakers of Westinghouse manufacture. Tests were made against the combined capacities of the Consolidated Gas, Electric Light & Power Company and the Pennsylvania Water & Power Company systems, and currents as high as 24,000 amperes at 13,200 volts were interrupted repeatedly. Tests on breakers of different sizes are described, the rupturing capacity ratings of the breakers referred to, ranging from 10,000 amperes at 15,000 volts up to 40,000 amperes at 15,000 volts.

Improvements of design and construction have greatly increased the ability of this type and make of breaker to handle heavy short-circuit currents and severe duty cycles. The demonstration connected with the opening of heavy short circuits, including oil throwing and gas ejection, has been controlled and the fire hazard greatly reduced. A positive means for preventing oil throw, while at the same time relieving gas pressures in breaker tanks, has been developed.

Data are given regarding tripping speed, length of arc duration, and condition of the oil and circuit-breaker structure after the tests.

THE electrical industry as a whole owes a debt of gratitude to the Consolidated Gas, Electric Light and Power Company and the Pennsylvania Water and Power Company for the broadminded and capable manner with which they have attacked the difficult problem of determining the capacities of heavy power house oil circuit breakers. While considerable testing of a similar nature had been done from time to time in the past, nothing approaching in scope the tests recently completed at Baltimore had been undertaken previously. These operating companies have in this work assumed large expenses and operating risks which could only be compensated for by the far-reaching results achieved.

The time was ripe for such a series of tests. Power concentrations have grown to a point where the capacity and price of switching equipment are serious considerations. Operating requirements also have become more diversified and actual test data under field conditions were needed to meet them. There has grown a strict demand for circuit breakers that will function satisfactorily under maximum operating conditions as the results of inadequate performance become more hazardous with the growth of switching equipment.

The breakers tested by the Westinghouse company were all of the dead tank form (see Figs. 5, 7, 9, 11) this being the general form of oil breaker built by this company for many years. The general features of all these breakers are the same, and the more significant of these are as follows:

All tank structures and mechanism parts are dead and can be solidly grounded.

All contacts, that is the main current-carrying contacts and the arcing tip contacts, are made and broken inside the oil tanks.

The breaker closes against gravity and opens with gravity, accelerated by spring action, both in normal operation and also in event of failure of closing power, failure of mechanical linkage, or failure of latch.

The purpose of this paper is to give the results which are of most general interest with some of the more important details. Briefly, the more marked improvements in this type of breaker, as a result of these tests, consist in:

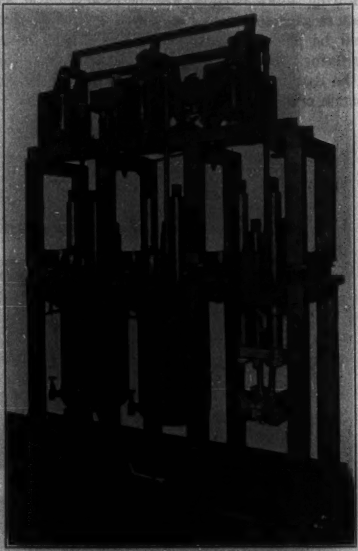


FIG. 1—ELECTRICALLY OPERATED OIL BREAKER SHOWING GENERAL FEATURES OF DEAD TANK BREAKERS
Westinghouse type 0-2, 4000-ampere, 15,000-volt.

(1) Decrease in energy losses within the tanks, with improved control of arcs and gases formed.

(2) Scientific relief of pressures generated combined with reinforcement of mechanical construction where necessary.

(3) Elimination of oil throwing.

Presented at the Annual Convention of the A. I. E. E., Niagara Falls, Ontario, June 26-30, 1922.

The result of these improvements has been increased rupturing capacity and ability to handle more severe duty cycles.

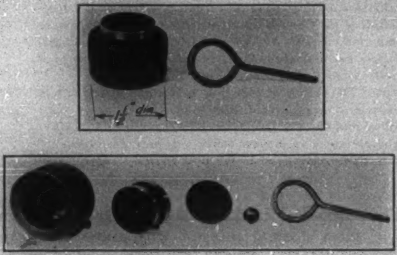


Fig. 2—Pressure Gage

Used in tests on Westinghouse Oil Breakers.

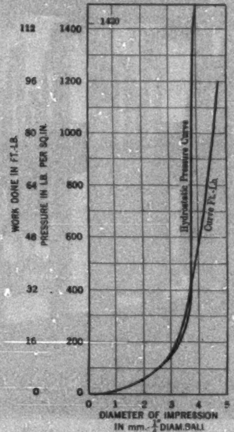


Fig. 3—Calibration Curve of Pressure Indicator

It was realized at the start that a knowledge of pressures developed in the tank structure at the time of rupturing short circuits was necessary. The small pressure gage shown in Fig. 2 was devised so that it could be placed in any location in a tank without interfering with the operation of the breaker as would be the case if the device were large enough to cause grounds or short circuits within the tank. This type of gage consists of a piston *a*, which is free to slide in a cylinder *b*, but the chamber *c* of which is sealed from the surrounding medium. The pressure in the breaker tank, acting on the piston, causes the ball *d* to make an impression on the lead washer *e* and the corresponding pressure can be read from the calibration curve shown in Fig. 3.

While the results secured from such a device are probably not accurate and have to be used with care, still they are very useful in determining the distribution of pressure over a breaker structure, and in determining relative pressures in breakers of different sizes and different types of design.

Quite early in the series of tests, it was found extremely desirable to provide ventilating and cushioning means for taking care of the pressures generated at the time of opening the circuit. It is realized that a considerable pressure in the tank is necessary to help quench the arc, but the more violent pressures due to gas explosions are not necessary for this purpose, and the ability of a given structure especially on repeated short circuits, can be increased by minimizing such pressures. The oil separator shown in Fig. 4 was developed for this purpose.

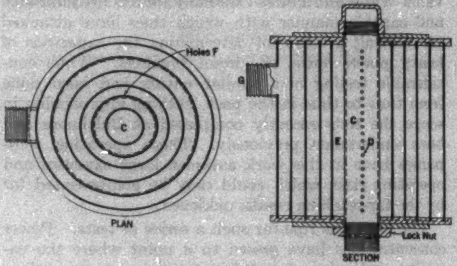


Fig. 4—Oil Separator

The oil separator was designed with the idea of ventilating gas mixtures, relieving pressures due to gas formation, and still preventing the throwing of oil from the structure. This separator consists of several concentric cylinders, the inside one being connected directly to the tank and the outside ones to the atmosphere. The mixtures of oil and gas entering the first chamber from the tank passes at high velocity out of the first chamber *c* through the row of holes *d*, and must then change its direction of flow in order to pass out of the second chamber *e* through the holes *f*, which are 180 degrees away from the holes *d* in the first path. In this way, going from the inner to the outer chamber at constantly decreasing velocity, the oil being acted upon by gravity drops into the bottom of the outer chamber and the gas flows through the vent *g*. With a properly designed oil separator, only a mist of highly vaporized oil escapes on the heaviest short circuits from the breaker structure with the gas, and the rest returns to the tank automatically by gravity as soon as the pressure is relieved.

The largest breaker tested was the Type "O-3" shown in Fig. 5. This is a three-pole electrically opera-

A

Tanks down—Pole covers removed.

B

Fig. 5—Westinghouse Type O-3 Oil Breaker
Three-pole, 1200-ampere, 25,000-volt, electrically operated

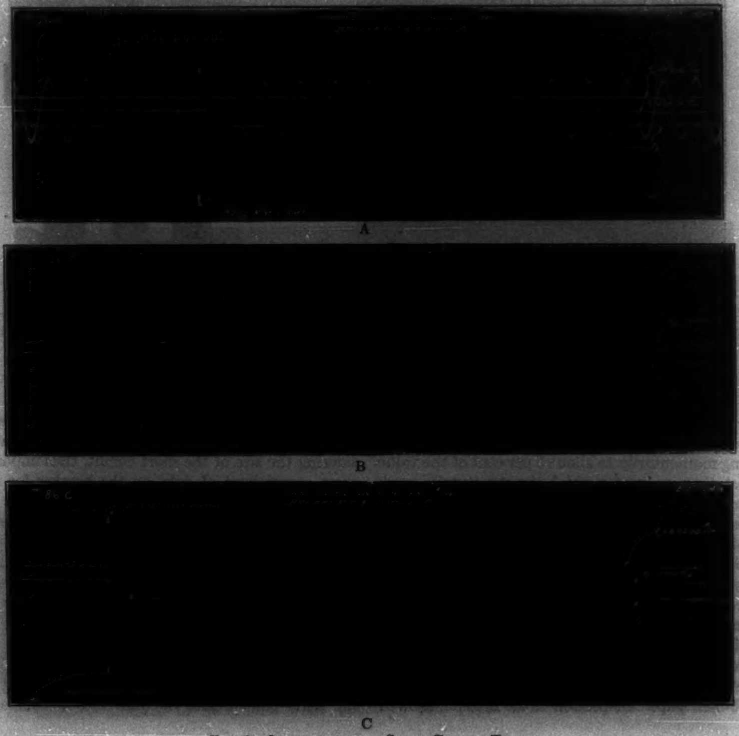
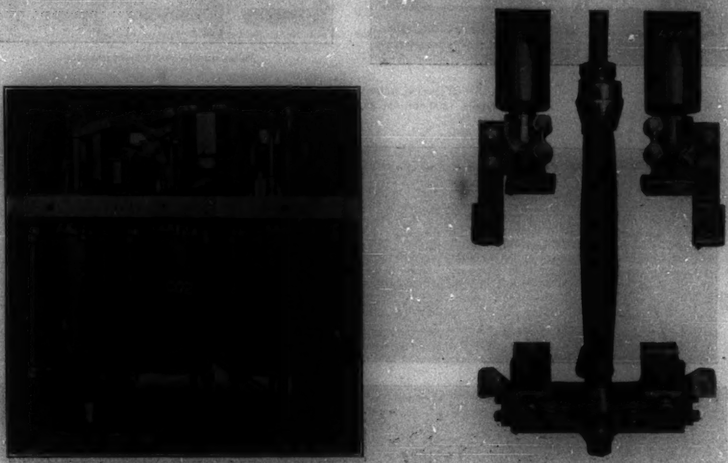


Fig. 6—Oscillograms of Short-Circuit Test
Westinghouse type O-3 oil breaker.

ted round tank breaker with condenser type terminals, parallel path contacts, and noninflammable insulating tank lining. The inside diameter of the tank is 24 inches. This breaker was subjected to eight short circuits on a system set-up calculated at 29,400 initial r. m. s. amperes. The current actually ruptured by the breaker varied all the way from 16,000 r. m. s. amperes to 24,000 r. m. s. amperes. The last seven short circuits were made in succession without inspection of the breaker, and the time elements between short circuits varied from 1½ minutes up to 35 minutes. Probably a small wine glass full of oil was ejected from the three poles during the whole eight tests, mostly in highly atomized form through the mufflers.

As the rupturing capacity rating of this breaker is 40,000 r. m. s. amperes at 15,000 volts, the pressure generated inside the tanks on these tests was small, amounting momentarily to about 5 per cent of the value of hydrostatic pressure for which the structure is good.



Arranged for test.
A

Contacts after seven short circuits (see text.)
B

Fig. 7—Westinghouse Type *C O*-2 Oil Breaker

Three-pole, 1200-ampere, 25,000-volt, electrically operated.

The arcing tips of this breaker opened three cycles after the short circuit was placed on the system, and the arc in all cases was completely ruptured within four cycles from the time the short circuit was placed on the system, the average being 3½ cycles (0.14 sec.). The average time of arcing was 0.5 of a cycle (0.02 sec.) with a maximum of one cycle (0.04 sec.). Samples of the oil used, taken from the three tanks after the completion of the test, broke down when stirred before testing at values varying from 14,000 to 24,000 volts on a 0.15-inch gap. Inspection of the breaker showed that deterioration consisted of burning on the arcing tips, singeing of the tank liners, and some pitting of the corners of the main brush. Later tests will show how pitting of the main contact was reduced. Fig. 6 gives a typical set of three-phase oscillograms showing line current, line voltages and ground current.

The ground current I_g is interesting as at times it rises to considerable values and is due to the arcs in the different phases being extinguished at different times as they reach the zero point of their respective current waves. In order to dispose of a question on which there has been some discussion in years past, we point out that in all these tests we have not found a case where the arc was not ruptured at the zero point of the current wave.

The oscillogram of restored voltage is interesting, showing that the system held up remarkably well considering the size of the short circuit, thus imposing the most severe kind of duty on the breaker for a given current. This was because the short circuit at Canton Substation caused relatively small demagnetization of the machines connected to the system. It is important to note that a large percentage of restored voltage may cause the reestablishment of arcing and consequently more severe duty on the breaker than if the restored voltage is small due to killing of the machine fields.

The type "*C O*-2" breaker shown in Fig. 7 has a cylindrical tank per pole 20 inches in diameter, and the three-pole breaker is built into a compact self-contained unit with tanks, terminals and mechanisms mounted on one steel base. It has parallel path contacts and condenser terminals. This breaker is a modification of the *"C O-2"* breakers now in general use.

This breaker was tested seven times in succession without inspection or alteration on a system set-up calculated at approximately 20,000 r. m. s. amperes. The current actually ruptured varied from 18,000 r. m. s. to 22,000 r. m. s. amperes. The arcing tips opened approximately 3.75 cycles (0.15 sec.) after the short circuit was thrown on, and the circuit was completely ruptured on the average of 4.25 cycles (0.17 sec.) from the time of short circuit. The time of arcing averaged ½ cycle (0.02 sec.).

Five of the seven short circuits were made in a total time of nineteen minutes to determine what effect operations in quick succession might have on the structure. The breaker threw probably a half gallon of oil from each tank during the set of seven tests, this oil coming through the oil separators. This particular oil separator was superseded by a superior design shown in Fig. 4, on subsequent breaker tests.

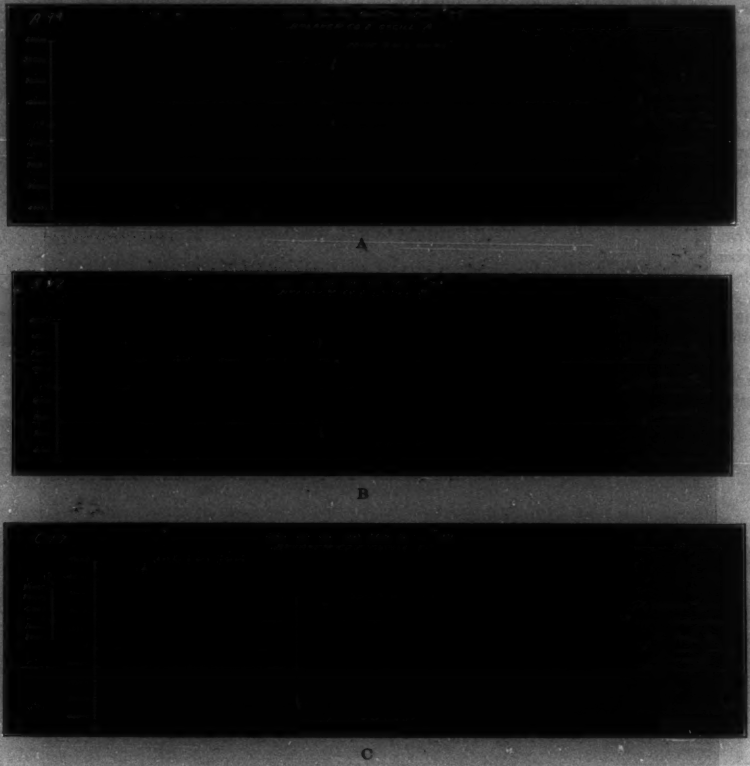


Fig. 8—Oscillograms of Short-Circuit Test
Westinghouse type *C O-2* oil breaker.

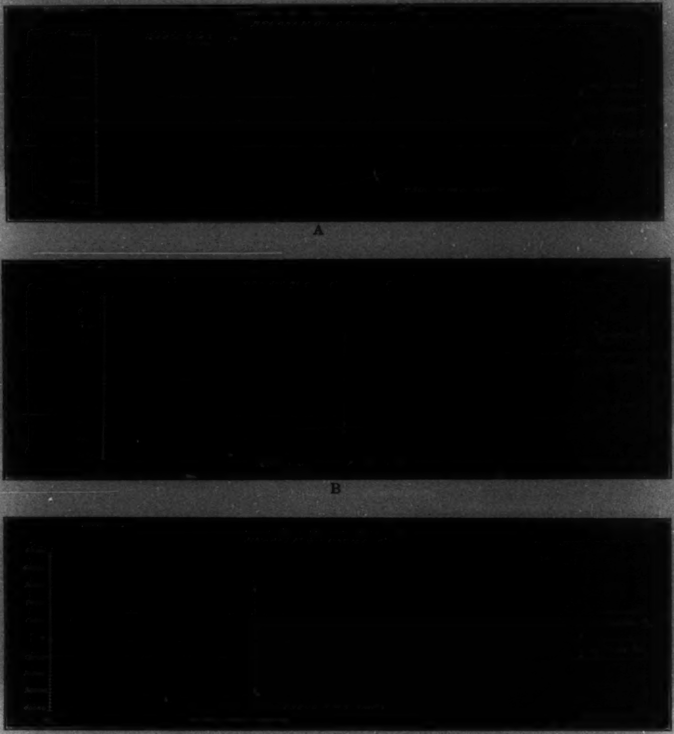
Deterioration of parts was limited to burning of arcing tips, pitting of corners of the main contacts, and a slight scorching of the fireproof insulating tank lining. Samples of oil when stirred broke down at values from 12,000 to 18,000 volts on a 0.15-in. gap. As closely as could be determined, the maximum instantaneous tank pressure was about 12 per cent of the value of hydrostatic pressure for which the structure was good. Fig. 8 shows a typical oscillogram of this series of tests.

The Type *"O-1"* breaker shown in Fig. 9 is a modification of the line now in general use, and was tested against a system set-up calling for 19,400 r. m. s. amperes, twelve times in succession. The first five short circuits were made in a period of eighteen minutes, and the last four were made in a period of four minutes without waiting for oscillograms. The other short circuits were made at varying intervals. Aside from readjusting a tank gasket after the fifth short circuit, the breaker was not altered during this period of tests.

The current actually ruptured ranged from 19,000 r. m. s. amperes to 23,900 r. m. s. amperes. The arcing tips parted on an average of approximately 3 cycles (0.12 sec.) from the time of short circuit, and the circuit was completely ruptured on an average of 3.6 cycles (0.144 sec.) from time of short circuit, making an average time of arcing of approximately 0.6 cycle (0.024 sec.).

The total amount of oil thrown from all phases on the twelve tests was approximately two quarts which came through the oil separators in highly atomized form. Samples of the oil when stirred broke down from 6000 to 7000 volts on a 0.15-in. gap.

Deterioration of the contact parts was limited to burning of the arcing tips and slight pitting on some corners of the main contacts. There was no scorching of the tank lining. Momentary tank pressures in some cases had run as high as ⅓ of the hydrostatic pressure for which the structure is good. Fig. 10 shows typical oscillograms of this series of tests.


A

B

C

Fig. 10—Oscillograms of Short-Circuit Test
Westinghouse type O-1 oil breaker.

The Type *"O E-6"* breaker shown in Fig. 11 has cylindrical tanks 14½ inches in diameter, and is built in single-phase units with a common mechanism and intermediate cell walls. This breaker was subjected to a final series of nine short circuits against a system set-up calculated at 19,400 r. m. s. amperes. The first five short circuits were made in a period of eighteen

Fig. 9—Westinghouse Type *O*-1 Oil Breaker

1200-ampere, 25,000-volt, electrically operated. Arranged for test.

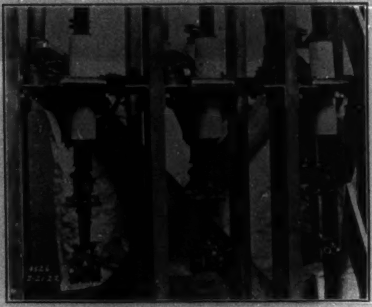
minutes and others at varying intervals. The current actually opened ranged from 16,300 r. m. s. amperes to 21,000 r. m. s. amperes. The average time from the point of short circuit until the arcing tips parted was approximately 3.25 cycles (0.13 sec.), until the circuit was completely ruptured the time averaged 3.75 cycles (0.15 sec.) and the period of arcing averaged 0.5 cycle (0.02 sec.). The amount of oil thrown was practically negligible, being limited to a few drops that leaked through gaskets from time to time, and a slight amount in highly atomized form through the mufflers amounting to half a cup full for the whole series of tests for three vessels.

The oil was extremely black and muddy at the end of the test, and while not tested for breakdown probably was not good when stirred up for more than 25 per cent of its original test value of 35,000 volts on 0.15-in. gap.

The deterioration of contact parts was limited to slight scars on the tank lining, and a rather slight amount of burning on the arcing tips considering the severity of the service. There was absolutely no sign of pitting or burning on the main contact members, as previous test had indicated methods for eliminating this pitting. Fig. 12 shows typical oscillograms of this series of tests.

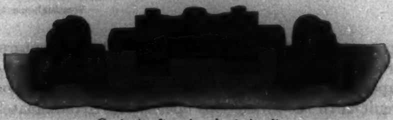
The modified Type "*E*-6" breaker shown in Fig. 13 is an elliptical tank breaker with the ordinary semi-

A



Showing condition after test.

B



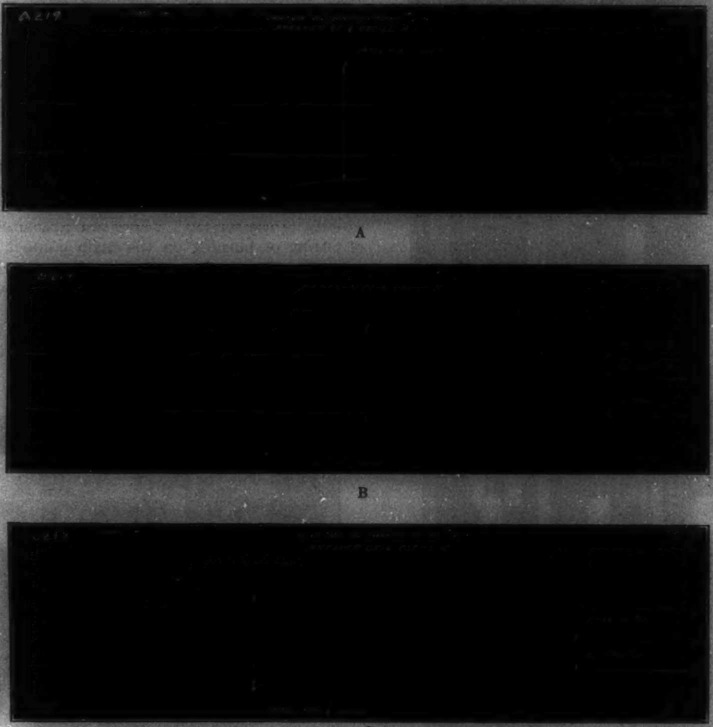
Contacts after nine short circuits.

C

Fig. 11—Westinghouse Type *O E*-6 Oil Circuit Breaker

Three-pole, 1200-ampere, 15,000-volt, electrically operated.

elliptical form of main contacts and combined porcelain and micarta terminal insulation. It is built in single-phase units operated from a common mechanism, and with intermediate barrier walls. The tests on this breaker are exceedingly interesting, as they indicate the possibility of elliptical tank breakers for heavy power house service where for lack of space, their use may be desirable.



A

B

C

Fig. 12—Oscillograms of Short-Circuit Test
Westinghouse type *O E*-6 oil breaker.

This breaker was subjected to a final test of ten short circuits on which the current actually ruptured varied from 10,000 r. m. s. amperes to 11,800 r. m. s. amperes. The average time from moment of short circuit until the arcing tips opened was approximately 3 cycles (0.12 sec.), the average time until circuit was completely ruptured was 3.75 cycles (0.15 sec.) and the average time of arcing was 0.75 cycle (0.03 sec.). The last five short circuits were made in a period of four minutes or an average of less than one minute between short circuits.

Approximately one-half gallon of oil was thrown from each tank through the oil separators on the ten short circuits, this breaker having been equipped with oil separators giving less back pressure in order to relieve the tank pressure. Some little oil leaked out around the tank gaskets.

Depreciation was limited to burning of the arcing contacts, slight pitting of the main contacts, and slight charring of the tank liners. Fig. 14 shows typical oscillograms of these tests.

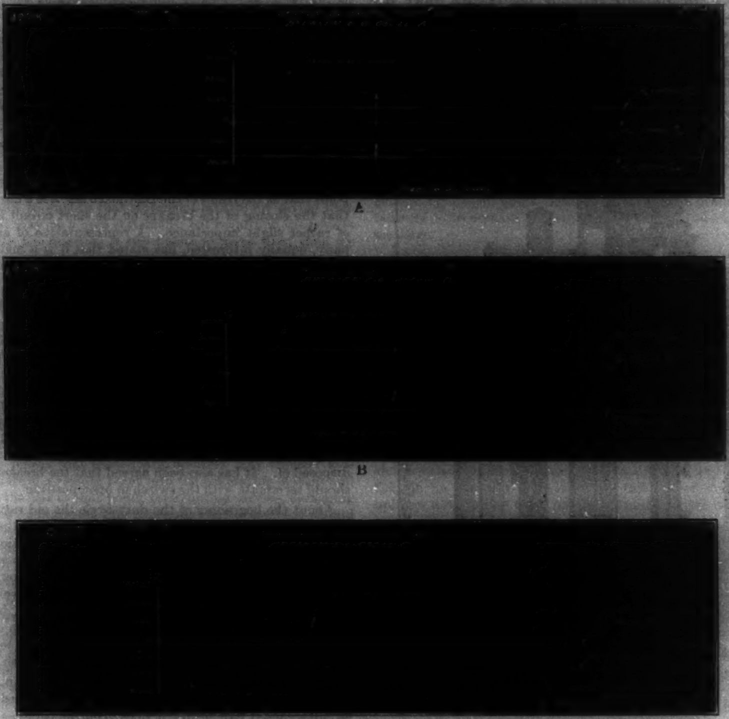
The results of the tests detailed above increase greatly our knowledge of the action of higher-power moderate-voltage circuit breakers of this make and type. We can not hastily draw conclusions regarding the action of breakers having different constructions and operating under different conditions from those actually tested. However, it seems these tests have been comprehensive enough to warrant drawing some conclusions.

It seems desirable from the point of view of securing maximum rupturing capacity in a given space that heavy power house breakers be equipped with means for freely venting large amounts of gases without at the same time throwing oil.

It is evident that designs can be produced which will be capable of opening heavy short circuits several times in succession with intervals either short or long between succeeding openings. In other words, the life of the breaker between periods of inspection and repair is principally a function of the amount of copper in the arcing tips.

With proper design, the condition of the oil does not seem as important as heretofore had been thought. This applies only to moderate voltage, heavy capacity breakers, such as those tested, and we wish to emphasize that regular inspection and good maintenance of oil is a desirable thing in connection with circuit breakers in general.

It seems that designs can be made in which the distress on the breaker on repeated short circuits is no greater than that on the first or second short circuit. This, of course, requires a construction which does not depreciate in any way with succeeding short circuits, outside of the depreciation of contact details and oil.



A

B

C

Fig. 14—Oscillograms of Short-Circuit Test

Westinghouse type *E*-6 (modified) oil breaker.

All the tests detailed above were made on 25-cycle circuits, and it seems probable that the rupturing capacity of a given breaker on 60 cycles is more than it would be on 25 cycles. The data show that on 25 cycles with heavy currents of the order of 15,000 to 20,000 amperes, the arc can be expected to go out in less than one cycle after the arcing tips part. On 60 cycles, the energy liberated in the tanks per half cycle is only two-fifths as much as on 25 cycles, and the opportunity for putting out the arc occurs more frequently on 60 cycles.

Circuit breakers can be made in which the oil content presents practically no fire hazard beyond that found in an oil-immersed transformer or feeder regulator.

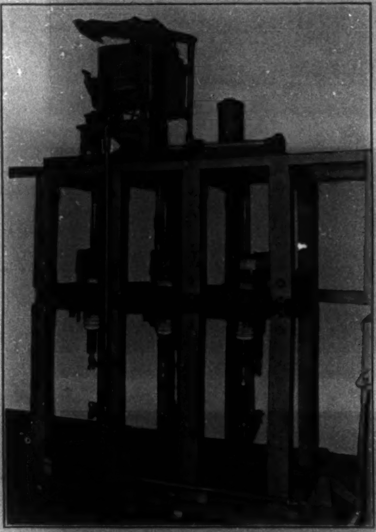


FIG. 13—MODIFIED TYPE *E*-6 BREAKER
Showing application of "oil separators."

It is well to call attention to the fact that sustained circuit voltage and high reestablished voltage are necessary to secure the maximum tests on a given breaker with a given service voltage. A truer criterion of the capacity of the breaker is the product of the current it opens and the voltage at the instant the contacts part. The severity of service also depends in many cases on the value of reestablished voltage. Very misleading results are likely to be obtained where these items are not taken into consideration.

In connection with the above test results it is desired to emphasize the effective and speedy arc rupture in all cases and the control of oil and gas throw by means of positive separating devices.

Discussion

DISCUSSION ON BALTIMORE OIL CIRCUIT BREAKER TESTS (LOUIS AND BANG),

TESTS ON GENERAL ELECTRIC OIL CIRCUIT BREAKERS AT BALTIMORE (HILLIARD),

TESTS ON WESTINGHOUSE OIL CIRCUIT BREAKERS AT BALTIMORE (MACNEILL),

Niagara Falls, Ontario, June 30, 1922

B. G. Jamieson: I would like to make an announcement which I was commissioned to make by the Subcommittee of the A. I. E. E. on oil circuit breakers. We have as a heritage a definition of duty cycle, which is fundamental in determining the rating of oil circuit breakers. That duty cycle, as defined by Hewlett, Burnham, Mahoney in a paper written about four years ago, represents the sumtotal of available literature on the subject. The adoption by the American Institute of Electrical Engineers of a standard definition is based on that paper.

Unless we know what the duty cycle is, we do not know much about what the breaker will do, because we cannot purchase and install breakers on an equitable basis.

One of the authors who presented a paper has emphasized the point that as the result of the Baltimore test it is a fair assumption that the closing of the breaker on the short circuit is something of rather slight importance. A representative of another company, equally interested, has stated that it is a matter of paramount importance. Whatever the facts may be, you will notice that in all circuit breaker tests conducted in this country, at least, the manufacturers have always been very careful to close in the "first" and use the second breaker.

I think we ought to know the facts on that point, and that brings me to a point I want to refer to specifically in connection with the announcement just made. The A. I. E. E. subcommittee on oil breakers has had a great deal of difficulty in defining specifically where the duty cycle should begin, and where it should end. It had some difficulty in putting into words in which there was no ambiguity, just what the condition of the breaker should be at the end of the test. That matter has been disposed of. It has also been agreed that the breaker duty cycle should terminate with the switch in open position.

About the beginning of the duty cycle the old ratings are said to have had for their intent the assumption that the duty cycle should begin with the breaker in the closed position, and that the standard rating of breakers is what is known popularly as two "shots." We are to understand that the breaker is supposed to be on the bus, and if opened once, it may be reclosed on the short, and open once more and then we are done, but we must know that the breaker is capable of being closed in on the short in the beginning. Some men have gone so far as to say that it does not occur, and others say it does not occur often.

There is another position which can be taken, namely, a breaker in a power station, 200,000 kilowatts, closed in on short circuits—and I can testify it does occur at times,—it seems almost preposterous to say that we should withdraw from the specification, that the breaker must be capable of being pulled on, on a short, and opening it, it must be assumed that the breaker was first on the bus.

Recently I sent out a questionnaire on this point and got some replies. Unfortunately, the opinions were about evenly balanced. The Committee instructed me to send out another questionnaire, with the purpose of getting an opinion from every operating man as to whether or not it would be better for the definition, at least the definition given in the American Institute rules, to specify or not specify the breaker as capable of being closed in, on the short. I will draw your attention to the specifications for the 3-shot and 4-shot breakers. In the case of the 3-shot breakers, at the 299th shot, the breaker must be closed in on the short, and the operator is supposed to close them on the first shot on the lower ranges.

We still have the option of operating breakers with the same degree of practical safety we have always had, it is simply putting the definition in the logical form, which will not require justification in the industry, either nationally or internationally.

I want to say that questionnaires will be framed by representatives of the A. I. E. E., the N. E. L. A. and the Power Club, so that there will be no doubt about the way in which this question is presented.

Referring now to these three papers, central station systems now require transmission system equipment of a few years ago for distribution, purposes. Immediate prospects of super-power systems behind this equipment and further electrification of industrial and railway systems beyond, focus our attention on those devices upon which the safety and thereby the practicability of this enormous energy combination depends. This makes particularly conspicuous the oil breaker, the most important of all protective devices.

The knowledge that these tests were being conducted during the past year or two and the realization of their importance has kept us in an anticipatory state of mind, and it is, indeed, gratifying to learn that in the opinion of those most concerned the result of these tests point to successful achievement in breaker design.

I would like to qualify that statement a little bit saying that whereas that may be a bare statement, but regarding the results of these tests, the question is still before us as to what shall we do with the vast number of breakers that we have on our systems, which are, at least, open to suspicion as to their interrupting ability. The various expedients that are being adopted, such as the installation of reactors and sectionalizing of systems are all practical enough, and very expensive, but it seems to me that what we are most interested in is not whether a breaker can be designed to interrupt a small amount of energy, but the question is—Can we afford to depend upon breakers for the isolation of defective portions of our system, or is the result going to be the development of a breaker we can afford to use? Perhaps that is not an Institute matter, but I feel it is at the bottom of a great deal of the trouble which we are now having.

When we reflect that inadequate breakers may transfer system trouble from a remote point into the generating station and possibly on the bus at that point, interrupting service, damaging property and endangering life, it is clear that everything should be done to establish fully the efficacy of oil breakers as a type, otherwise our protective engineering is but a grim travesty. At this point I would like to explain that the word "inadequate" does not mean defective; it means insufficient, which is often as chargeable to the operator as to the manufacturer, perhaps properly more often.

It is essential also to determine the functional capacity of oil breakers as energy interrupting devices in order that other elements of the system or new devices may be made available to compensate or substitute for the conventional types of breakers beyond their established limitations. By that I mean that when some little device which may now be in the minds of research men, makes its appearance and makes big circuit breakers look like a joke, the sooner we know about that the better.

Referring more specifically to the data as published in these papers, several important factors stand out. First, all short circuits were made beyond the closed test breakers. This method of test seems to some of us illogical, particularly so in consideration of the duty characteristics of reclosing breakers which are required to close in on a short as well as to interrupt the short circuit.

I am not advocating the repeated closing of heavy duty breakers. I agree with Mr. MacNeill that it is unimportant, relatively, to the operator, to know what a breaker will do five or ten times. It does not matter whether the breaker stands up or not, but such service as that in a commercial system is beyond the requirements. The effect on the system, drop in voltage, and loss of synchronism, produces a mechanical stress, and weak points which no one suspected, may be developed. I desire to repeat the statement, that is, what we should know is what a breaker will do once. I do not say that we should buy a breaker on that basis, but we should know if breakers, for which we pay thousands of dollars, will do the things they are designed to do in an emergency which occurs seldom.

There should be no uncertainty as to how a breaker in a switch center of a large system will perform if it be closed in on a short circuit; the fact that such an event seldom occurs, notwithstanding. The importance of the successful performance of the breaker under such conditions is of such an order that there should be no question about its functioning. On the other hand, all tests were made with dead metallic shorts. This is an extreme condition which is seldom met with except when the breaker is closed in on a short by reason of some wrong connections. It is difficult to conceive of a dead metallic short (other than grounding devices) simultaneously established on three phases in a modern power house. Cable dielectric faults perhaps come closest to such a condition, but the average cable fault is usually at some distance from the power house. At this point I would like to call the attention of operating men to the great hazard of grounding generating station buses, more particularly the practise of simultaneous three-phase grounding which underlies modern methods.

In the Louis and Bang paper the fact was brought out that 77 per cent of normal voltage was re-established immediately after the arc. That is interesting and together with the statement that the larger percentage of short circuits seemed to break at the zero point corresponding to the time at which the stored energy is a minimum, are very significant, and would undoubtedly be the subject of a very profitable discussion, particularly for those who have in mind future tests on the same general order. If it is a fact having general application that tests may be more properly conducted at a point remote from the generating center, then tests of this sort may be combined with tests on relays, reactors and other protective devices functioning with the breaker. Also, reference to the effect that single and two-phase shorts caused severe vibration of generators, and to the effect that in no case did the generators fall out of step, are in my opinion noteworthy facts having a fundamental bearing on the results recorded in this series of tests.

Please consider these two facts together with the previously stated fact, that the tests were made by means of dead metallic shorts on a system having a solidly grounded neutral.

Now what I desire to bring out is that while we have obtained performance data of great value, in connection with certain types of breakers functioning under effects of short circuits, systematically applied, and obeying very closely their natural decrement laws, with generators supplying the energy in rythmic harmony, and with voltage transients apparently suppressed, that unless more definiteness is given to the effects of short circuits originating as single-phase faults and undergoing cycles of reestablishment, of generators out of phase with one another, as a result of the short and with voltage transients present, we may have our oil breaker rating based on "average" arc amperes at normal voltage brought into question.

In the paper by Mr. Hilliard an italicized statement on the first page seems at first reading to rather tend towards a discounting of the value of these tests by its restricted wording. Most engineers will understand what was intended by this statement, but it will be unfortunate for the art if an interpretation to the effect that these tests were special gains currency, thereby minimizing their value for deductions of a general nature. It is noteworthy that the duty cycle on the breakers included five successive interruptions at two minute intervals instead of the conventional number of two.

Statements that oil deterioration is not the factor which will determine the number of interruptions that can be made is comforting to know, if it is a fact that has general application. Combining this statement with the expressed assurances of the manufacturers that they are able to prevent the throwing of oil, and with the statements made elsewhere that tanks can be built so there is no danger of bursting, we find that the problem of successful breaker operation is reduced to the maintenance of arcing contacts, which the manufacturer unreservedly applies to oil circuit breakers of any type; this, then, becomes the crux of the whole matter, particularly where the duty cycle of the breaker requires repeated operation.

The paper by Mr. MacNeill imposes less restrictions than the paper by Mr. Hilliard insofar as the making of deductions from the results of these tests is concerned. The switches tested were of the general form of oil breaker built by the Westinghouse Company for many years, the improvement being largely in methods utilized to prevent throwing of oil and the relief of pressure caused by the arc gases. It is of interest to note that the author is able to point out definitely that throughout the test the arc was always ruptured at the zero point of the current wave. This assumption has been questioned at times in the past.

The suggestion of a differential rating for switches on 25 and 60-cycle service is another point which it seems to me to be worth considering in the determination of switch duties.

Attention of committee members is also directed to the statement of the author in the closing section of his paper regarding the effect of sustained voltage in imposing the maximum duty. As is stated, very misleading results are likely to be obtained in calculations of circuit breaker duty or performance where sustained or re-established voltage values are not given proper weight. This point appeals to me particularly in connection with private and committee work where failures of breakers have been reported. I think it is safe to say in general operating systems are woefully short of the proper registering devices to enable definite statements to be made regarding the successful or unsuccessful operation of breakers on system disturbances.

In closing, following a thought suggested by the specification appearing on the first page of this paper, which reads "all tank structures and mechanism parts are dead and can be solidly grounded," in consideration of recent experiences and previous convictions of the operating personnel of our own company and with due regard to the development of iron clad central station switch gear, I believe that the art of developing safe oil breakers on systems backed up by heavy power will be a problem of considerably less magnitude accordingly as we remove solid grounds from proximity to the arc rupturing elements of the present conventional type.

A. A. Meyer: Regarding the risks the central station companies should assume for conducting oil circuit breaker tests, I might call attention to the tests which were made by the Detroit Edison Company about five years ago. These were similar in many repsects to the Baltimore tests, and while they were not so numerous, they were of about the same magnitude.

One feature I think should be pointed out here, viz., that the large connected kv-a. capacity which was mentioned in connection with the Baltimore tests, was not all concentrated right at the point of the short circuit. In addition to the limited generator capacity at the short, there were several inter-connected feeders several miles in length and having an appreciable impedance.

Another item worthy of notice, is the fact that these tests were conducted usually on Sundays or nights, and during light load periods. You will appreciate that the magnetic energy being stored in a generating system during the light load periods, is of a small order and not so detrimental to the opening of the arc by a breaker, as that during the heavy load periods. This was demonstrated in some of the Detroit tests.

I might add that tests on the 24,000-volt circuit breakers, and of such magnitude as conducted at Canton, are being made occasionally in Detroit at the present time. I say occasionally, and also inadvertently, if you please. Our breakers in service have been recently subjected to duty of an order as high as 700,000 kv-a. and without any damage to the breaker.

I am pleased to note that the tests were conducted with the aid of so many measuring instruments. These are very essential in obtaining reliable data, which may be used for comparison with previous results, as well as with results to be obtained in the future.

It is unfortunate that some of the data obtained in these tests are being withheld from publication. Only such data have been published as concerns directly the latest type of breaker developed from these tests. There are considerable more data covering the older types, which have an important bearing on the circuit breakers which are so extensively installed in the various systems at the present time. Operating engineers are vitally concerned in the circuit breakers in service, and should have all information in order to take advantage of any improvements which might be applied to the present equipment. This is being denied and apparently for commercial reasons.

W. L. Wallau: A year ago in Cleveland we made a few tests in a minor way. We were not equipped with oscillographs, but we had certain conditions that we wanted to meet. We wanted to see if certain switches, which were inadequate on our 11,000-volt system, might possibly be used on our 4600-volt power distribution system.

With 125,000 kv-a. connected to the generating station bus, we made tests at a substation some four miles distant. This substation was supplied by seven No. 4/0 cables operating in parallel, and the 4600-volt system for test purposes was supplied by three 3000-kv-a. stepdown banks. The switches themselves were connected to the secondary side of these banks in parallel through about 90 feet of 0000 cable. The load on the station, was about one-third of the generator capacity. These tests were carried out successfully without any undue disturbances on the system. The only trouble that developed was a ground on one cable, which was a self-healing puncture.

What prompted us to make the test was that we had this same condition to meet inadvertently whenever a short circuit occurred on one of our 4600-volt power lines, close to the substation. Why should we not try to learn something from tests? We did learn that the particular switch that we wanted to use was inadequate even for a 4600-volt service. That was due to the larger current which it had to interrupt due to transformation ratio, as compared with the manufacturer's rating at that voltage.

The actual initial short-circuit current was of the order of about 15,000 amperes, and several types of switches were tested, and among them one switch with a very light mechanism which operated very speedily, and that switch stood up better than the others and we were able to repeat a short circuit on that particular switch with four banks of transformers, giving about 18,000 amperes initially.

I think, perhaps, all of us have been a little too conservative in offering our systems for experimental work, too much afraid of what was going to happen to the system. If we start to analyze our own conditions, we will see in our occasional short circuit that we have just as severe conditions as you would meet with on test. We may have a short circuit, which possibly results in a wrecked switch, but we do not wreck all the system, by any means, and do not anticipate we will wreck the system every time we have a short.

In this particular system, on the 11,000-volt bus, it is possible in almost any substation to get an energy supply on short circuit in the neighborhood of half a million kv-a., and as we operate our transmission cables to substations entirely in parallel, it puts a very heavy duty on any of the breakers, and the substation breakers may open under reverse power to clear a fault in the cable fed by seven, eight, ten or even twelve lines.

I want to emphasize Mr. Meyer's point, the papers have not told us much about the troubles experienced. After all, the troubles are what we are interested in mostly, as much as the optimistic results which the manufacturers feel they can obtain later.

Another thing we are interested in knowing is what can we do with the breakers on our systems to modify them so that they can be used where we want them. In the past I have had occasion to report a large number of failures on the G. E. K-12 breaker, and I would like to say the failures reported were not in the nature of criticisms. We knew that the breakers were inadequate for the work they had to do, and we reported that to show how successful they had been in interrupting currents in excess of rating.

A. H. Sweetnam: It would seem to us that no operator could consider an oil circuit breaker, especially if it be on a one or limited shot basis, unless it be with the understanding that the duty cycle be "open, closed and open," as the breaker might at any time be required to close on a faulty line. One large operating company serving certain sparsely settled territory finds it necessary to operate, non-attended substations supplying from 1 to 2 distribution circuits. The transmission lines supplying such substations are fed from an attended substation bus and are equipped with automatic oil circuit breakers which will function in case of faults up to or beyond the non-attended substation. In such cases it is the practise after the automatic transmission line breaker has functioned to reclose it and if it again opens to reclose a second time, after which it is left open until the fault has been located. This plan makes possible the serving of business which otherwise could not be signed on account of high operating costs.

Many lines are radially operated, certain lines being normally in service and others held in reserve. We believe that many operating companies find it necessary to try a line by reclosing after the breaker has opened automatically and this appears to be a case parallel to that cited above; hence our conclusion that the duty cycle be defined as "open, closed, open," as any other definition would require the installation of a breaker designed for heavier duty and consequent greatly increased cost.

A. H. Hull: As you know the Queenston plant now being built will contain five 45,000-kv-a. units. When we started the short-circuit studies, we were contemplating an installation of nine such units. On that basis we estimated we would have on the 12,000-volt circuits, in the case of a fault, approximately 70,000 r. m. s. amperes and in the case of a fault on the high-voltage circuit, approximately 6700 r. m. s. amperes, at 110,000 volts.

I believe that the requirements for circuit breakers for that service are considerably in advance of installations that have been made in hydroelectric power plants. We bought two types of breakers for the 12,000-volt circuits, the Canadian Westinghouse Company's type C-4 and Canadian General Electric Company's type F. H. D. 21-Y.

While it is not anticipated that we will operate with nine units in parallel, there may be times in switching operations on the system when it may be necessary to operate eight or nine units in parallel for a short time. We have not had the opportunity of making short-circuit tests on the system, and we have been rather hesitant about accepting the ratings that have been put on the rupturing capacity of the breakers. We hope in the course of the operation of the plant to get experience with both types of low-tension breakers, that will give us, at least, comparative results, and results from which we can extend the station as now contemplated with considerably larger generating units.

One feature in connection with these breakers, which we considered very important, was strong tanks. Those on the 110,000-volt breakers that are installed are required to stand an internal hydrostatic pressure, with the bushings and cover in place of 250 lbs., per sq. in. The Westinghouse type C-4 breaker tanks are required to stand a pressure of 500 lbs. per sq. in. They have 36-in. diameter tanks. I would like to know from the tests reported from Baltimore, just what pressures were obtained in the tanks on these tests. We have a reference in the paper to the fact that pressure tests were made, and a statement that the pressure approximated one-third of the hydrostatic pressure, for which the structure was designed. That does not tell us very much.

Another feature on which I think we ought to get further information is how the breakers will take care of phase to neutral short circuits.

At Queenston, we are operating now with the generator neutrals solidly grounded. We have had no shorts there, but have had other cases where we had shorts to neutral, and also cases where we had metallic three-phase shorts on which the breaker has been closed. I think further information on the question of phase to neutral shorts is desirable.

A. F. Bang: In connection with the Baltimore oil switch, I would like to point out a few operating features which have a very distinct bearing on the performance of breakers. I refer particularly to the influence of the relay setting, the influence of having parallel feeders, and the influence of the arc in an arcing short. I think it is well to call attention to these operating conditions, so that we can realize that at least as far as opening a short circuit the Baltimore tests were actually extremely severe. I think too if we consider these facts, that to some extent they will explain why we actually have been able to get along fairly well for so many years with breakers which we knew were not quite up to the rupturing capacity of the system which we were dealing with.

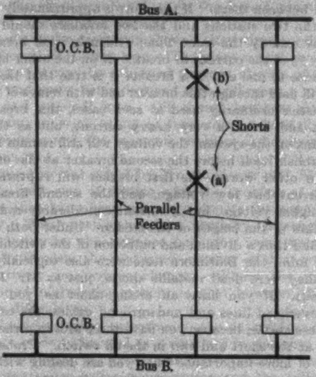


Fig. 1—Single Wire Diagram of Parallel Feeders

I will dwell first on the influence of the time element. In most power systems the minimum time of relay operation is about one-quarter of a second, and in many cases that time element is increased the closer you get to the generating station. That, of course, means that where you get the highest current you have the longest time. That is not done intentionally for easing the task of the breaker, but simply in order to secure selective relay action. Incidentally, it means though an easier switching task for the breaker for several reasons. In the first place, a dead short circuit usually begins with a very heavy value and then gradually dies down, due to the demagnetizing of the generators. In some systems the current in one second may perhaps die down to one-half value. And for the same reason—that is, the demagnetization of the generators—the voltage which will establish itself across the switch contacts, at the moment the arc is broken, will be proportionally reduced. That means only one-quarter of the rupturing task for the switch which you would have had if the breaker tested opened at the first instant.

There is a third item which comes in. If you delay the opening up of the breaker, it is possible that some of the synchronizing equipment may fall out of step. If that happens, that will draw some of the current away from the short, and will keep the voltage down, while the breaker is opening. That, too, means a reduced switch duty. In some cases it is quite possible that the synchronous equipment, which was out of step, may be pulled into step again *after* the breaker has opened up, and when you come to look at it, you cannot understand how a small breaker seemingly successfully broke an enormous amount of current. The fact is that it was favored extremely by circumstances.

Now as to the influence of parallel feeders: These tests in Baltimore were all made on a radial feeder. In many cases we do not have such a condition, but are dealing with a number of parallel feeders, each connected through to a station bus. If a short circuit takes place on one of these feeders it is clear that none of the breakers *A* or *B* (see Fig. 1) will be called upon to interrupt the full amount of the current, but it will be divided in some way between them. If the short is approximately midway between the two stations and the two breakers should happen to open at exactly the same time, evidently each breaker will have only ½ of the current to break. If on the other hand, the short is close to one end of a breaker it is true that the greater current will pass through this breaker and with relays of the time characteristics ordinarily used in such cases, this breaker will open first and break a very heavy current, but as the short still remains on the system, the voltage will still remain low, and not reestablish itself before the second breaker at the other end opens. In other words, the first breaker will rupture a very heavy current but low voltage, and the second breaker will break a higher voltage, but a current considerably reduced by the insertion of the length of the feeder. Under both assumptions we find thus a division and reduction of the switching task.

To my mind the Baltimore tests were also especially severe because they were dead metallic shorts, just as Mr. Jamieson pointed out. If you have an arcing short as you will get both on overhead lines and underground cables, the conditions must be less stable, because you have three arcs in series in that case, one at the short and two in the oil switch. Probably this feature is of more importance when you are dealing with lighter short circuits, where the arcs generally are less stable than when you are dealing with very heavy ones. In Baltimore we still expect to look further into that particular phase of the question, and also some of these questions regarding the influence of paralleling of lines and delayed time settings.

E. R. Stauffacher: These short-circuit tests are indeed interesting to us. We, in the West, are approaching the conditions of the central stations in the East in a number of territories. The main difference, however, is that our operating voltage is much higher.

You have been speaking of interrupting capacities of 500,000 kv-a. and 650,000 kv-a. From some of the results we have had in our stations and from the calculations we have made, the amount of current that certain switches on the system of the Southern California Edison company must interrupt is fully as great.

At our Newmark substation, located near Los Angeles, four 66-kv. double-circuit transmission lines feeding from four different points are brought to a common bus. It has been calculated that there are approximately 6000 amperes flowing at the time of a short circuit on this bus. A few cases have occurred where disastrous results have justified the calculation. It appears as if our 60-kv. network system must, some day, be changed to a 110-kv. system. At the present time both of our 150,000-volt transmission lines are being changed. We are raising the towers and adding insulators and shield rings so that we expect to be operating at 220-kv. by the latter part of this year.

Oil circuit breakers for voltages as high as 220 kv. are somewhat of an experiment. The manufacturers have been very kind in furnishing their best talent and in giving us the latest engineering information on this subject. We are waiting with interest the results of breaking a short circuit of approximately 2000 amperes at 220 kv. which will be the condition on our Big Creek transmission line, for if the switches do not handle the situation it will be quite a serious matter. This condition, that of the use of higher voltage circuit breakers, appears to be the greatest difference between our Pacific Coast and the eastern application of oil circuit breakers.

F. C. Hanker: In recent years, the importance of mechanical strength of structure has been fully recognized, the most important advance in that phase of design resulting from a similar series of tests made in New York and reported to the Institute. These tests differed from the present series in that they were for the purpose of establishing the mechanical sufficiency of the structure under the magnetic stresses resulting from heavy current conditions. The modifications made, following the New York series of tests, have been embodied in the later designs and it is of interest that the types used in the Baltimore series showed no distress from this point.

The oil circuit breaker tests at Baltimore have re-assured the operating companies as to possible hazard from making such tests and they realize that it is essentially a duplication of their operating condition. We trust that in the future other operators will take advantage of the results of these experiments. I was interested in reviewing the field tests that has been made in the past. Mr. Meyer referred to one on the Detroit Edison System in 1915. The test on the Niagara Falls System across the river probably represented the next highest capacity concentrated. This test was made in 1911 and was with from one-quarter and one-fifth of the capacity used at Baltimore. Previous to that, we had tests on machines of single units, isolated on separate bus sections of 11,000 and 12,000 and up to 30,000 kw. concentrated. Some of the tests made across the river on the hydroelectric plant had the cable system connected and in effect were similar to the Baltimore tests except in magnitude.

As Mr. Meyer pointed out, those at Detroit gave essentially the same concentration of power, the only difference being that they were not as extensive as the Baltimore tests. At Baltimore, they had on the order of 170,000 kw. connected. The short-circuit current was limited, as Mr. Louis indicates, by series impedance in order to give the desired values at the Canton substation.

Mr. Meyer mentioned the amount of magnetic energy in the machines. As a matter of fact, that has considerable bearing on the restoration of voltage, but the flux condition in the machine must be the same with the same induced voltage. This is clearly demonstrated in the values of reestablished voltage that were on the order of 80 to 90 per cent of the system voltage. The number of high power tests will probably be limited to a few large systems, and they will certainly be increasing when you consider the amount of interconnection.

Distinct developments have resulted from each series of tests that have been made in the past on systems of operating companies where conditions the same as those obtained under actual operation are found. In the present instance, the changes have been of a minor character, proving that the fundamental principles are correct. Fortunately, sufficient time was available to test the modified structures to definitely prove the correctness of the improvements.

It is difficult to obtain from papers that have been presented an adequate conception of the magnitude of the work that has been done and of its importance to the industry, especially when you consider that the fundamentals of the designs have been unchanged. It is particularly important that the adequacy of the breaker structure has been confirmed. When you consider, the enormous energy that may be concentrated in an abnormal, the necessity for having a structure that has a large factor of safety in rupturing capacity and mechanical strength to meet the most severe conditions is fully recognized.

In recent years, there has not only been an increasing growth in the size of power stations but a marked increase in the total capacity of systems resulting from interconnections. The advantages from unified operation are so well established that there will be an increase in the total system capacities, making it essential to have adequate interrupting devices to insure continuity of service.

As a result of the uncertainty that has existed in the past, as to the adequacy of the very large circuit breaker structures on moderate voltage systems that are installed indoors, there has been a tendency to consider designs of structures to provide against the possibility of failures in the circuit breaker parts that might cause breakdowns on adjoining circuits. These studies have resulted in two notable examples using the so-called segregated phase layout. At present there are several stations under construction or being designed where careful study has been given to the advantages and disadvantages of the latter schemes. It would be very valuable for the Institute to have the benefit of the conclusions that have been arrived at by the various engineers.

The sufficiency of the breaker structure has been clearly demonstrated in the Baltimore tests and it will be of interest to determine whether operating engineers consider it necessary to resort to phase segregation in order to provide against a spreading of trouble to adjacent circuits by complete separation. The other parts to be considered are the bus structure, the disconnecting switches and the current transformers. A number of failures have resulted from faulty operation of the disconnecting switches and it is necessary that designs should embody features that will overcome such difficulties. In recent installations where switches are mechanically operated and interlocked with the breaker mechanism this should be sufficient precaution against such failure.

In the last few years there has been considerable criticism of the standard rating adopted for circuit breakers following the presentation of the problem in 1918 at the Mid Winter Convention. It is to be hoped that a full discussion is secured so that the requirements of operating companies can be crystallized and ratings be standardized for a minimum number of conditions. In past discussions, it has been difficult for the operators to agree on the ratings necessary to meet the varied conditions of operation for different classes of service. It is to be hoped that the discussions at the present sessions will clarify this situation.

H. H. Dewey: Tests of oil circuit breakers have been made from time to time that have been valuable in giving the manufacturers data on which to base their designs, but often these tests have been so limited as to the amount of energy in the short circuit or the completeness of the data recorded as to leave opportunities for differences of opinion on the interpretation of the results. The tests described lack none of these features and we may well feel that a most important step has been taken toward the ultimate solution of this most important phase in the development of our large power systems.

It seems like heroic methods to subject a power system of 150,000 kw. capacity to a succession of heavy short circuits, but the results of this investigation show that it can be done without serious risk to apparatus or service if done systematically and with due regard to the protection of the system from secondary failures. I have no doubt that other operating companies will be less hesitant in making similar tests in the future.

One of the most gratifying results of the tests, it seems to me, is the indication that the manufacturers have not been so far wrong in their ratings of switches of standard design. Practically all of the switches tested performed well and only slight modifications were necessary to show most satisfactory results.

The rapid growth in the generating capacity of our power systems has put the problem of the selection of oil circuit breakers squarely up to the electrical industry and the greatest difficulty has been encountered in keeping up with the growth of these systems. There are undoubtedly thousands of switches in service today that would fail if a dead short circuit should occur at their terminals. Operating companies are replacing these switches as rapidly as possible, but physical limitations and the expense involved render this necessarily a slow process. It is surprising that as few of these oil circuit breakers have blown up, with disastrous results, as have, but the answer is, doubtless, that the short circuits have not occurred. Some of the reasons why they have not occurred were brought out by Mr. Bang; such as, the fact that not all short circuits are of full theoretical value, the recovery voltage is not always complete, systems may normally be partly segregated, etc.

We are gradually growing to the point where greater and greater short circuits are being imposed on our systems and it is becoming increasingly important that study be given to the initial layout of the system connections, not only so arranging the circuits as to take full advantage of the neutral reactance of apparatus and connecting lines but by judicial use of reactors to keep the short-circuit values to the lowest practical value consistent with good operation.

The tests under discussion showed short-circuit values of the order of one-half million kv-a. There are several systems now operating that may be subjected to short circuits of this value or more and many being designed that will reach a million or a million and one-half kv-a. Oil circuit breakers designed to safely interrupt such values as these must necessarily be large and expensive and the economic problem is becoming a most important one.

The question was raised by Mr. Jamieson and Mr. Meyer, as to the best way of dealing with the problem of old circuit breakers that have been outgrown due to increase of system capacity. This question has been partially answered by both manufacturers by the evidence from the tests that they can materially increase the rupturing capacity of their switches by comparatively inexpensive changes. Where the increase in the required interrupting capacity is great, however, the problem is a very difficult one.

Mr. Jamieson called attention to the desirability of settling on a duty cycle to be used as a standard in selecting oil circuit breakers. The N. E. L. A. and other technical bodies have this matter under active consideration and the difficulties are gradually being clarified. It is hoped that an analysis of the Baltimore test results will throw some further light on the matter and an early settlement may be made.

I hope that as time goes on, we will see further tests similar to those made at Baltimore where elaborate preparations were made to obtain definite and accurate data. Such tests are of inestimable value and the very fact that some 200 short circuits were placed on the system without serious damage to apparatus or service, should lead to further tests of this kind.

M. J. Lowenberg: I have witnessed several cases where oil circuit breakers were closed on a three-phase dead short circuit, in one case at the bus two minutes apart on a system having at the time over 220,000 kw. in generators running and where the breakers functioned successfully without disturbing any synchronous apparatus or service.

Some one asked what we are to do with our old breakers. I think that what we should do is to maintain and inspect them especially after a very heavy duty. It does not cost much to produce very good results in this way. The Interborough Rapid Transit Company have some old type *H* breakers on a system of anywhere from 250,000 to 300,000-kw. generator capacity on the busses with a like amount of synchronous converters, where they have had very heavy short circuits that were cleared in every case with no serious trouble to the breakers or equipment. This performance is due not only to the character of the breakers but also to the rigid inspection and maintenance of the breakers.

I would like also to call the attention of the manufacturer to breakers (on systems of less than 6600 volts) which should have a better balance than they now have between heating capacity and rupturing capacity. Take for example a breaker operating at 2300 volts. You will find the breaker is limited by heating capacity and not by rupturing capacity.

L. B. Chubbuck: Referring to the oil separator described by Mr. MacNeill it may be of interest to state that separators of this type are furnished with the tank type 12,000-volt breakers at Queenston. One separator 8-inch diameter by 13 inches high is used per pole, the exhaust from the separator to be connected to station vent pipes, to prevent accumulation of gas in the circuit breaker rooms. It is our experience that without such separators, low-tension breakers under severe service, are liable to blow gaskets or throw excessive oil with ordinary vents. Tank structures can be furnished of sufficient strength to meet the arc gas pressures corresponding to the breaker rating. High-speed operation, properly designed and submerged contacts, strong, non-fragile bushings and arc-proof insulating tank linings, are also important factors. The Queenston tank structures are designed for an ultimate strength of 1000 lb. per sq. in. internal pressure and the condenser bushings to meet a cantilever test of 5000 lb. applied at either end of bushing.

We have had a number of instances in Canada of breakers failing, not due to pressure from arc gases, but from gas explosion above the oil. Such failure is not possible with the larger, later designed low-tension breakers, owing to the tank structure strength required to meet their rupturing capacity. However in the case of high-tension breakers we find possible gas explosions the chief hazard to the strength of the breaker, and for this reason furnished the Queenston high-tension breaker tanks of an ultimate strength equivalent to 500 lb. per sq. in. internal pressure.

O. H. Eschholz: Breaker distress has been shown in these tests to be primarily a function of arc energy and the character of arc gas control. While the rupture duty, I wish to call your attention to, of direct-current circuits is dependent upon the formation of an unstable arc, the interruption of the alternating-current circuit requires the prevention of arc reestablishment after zero current has been reached. The former necessitates a continuous increase in arc resistance, the latter an exceedingly rapid change from a medium of low to one of high dielectric strength.

An inspection of the current waves in the various oscillograms secured reveals the important fact that the arc current changes but little during the rupture period. To minimize arc energy and hence breaker distress it is therefore necessary to maintain a low-voltage arc and to decrease arc duration. Various expedients may be adopted, either in the construction of arcing contacts or in the control of pressure variations of the arc enclosing medium, to assure a low arc voltage during current flow. Obviously, a decrease in energy development decreases gas evolution and hence simplifies the problem of preventing arc reignition. It may be of interest in this connection to note that with some of the constructions adopted it was possible to consistently restrict arc duration to one-half cycle when rupturing currents of the order of 20,000 amperes. While of no practical need at the present time, it is interesting to know that by properly choosing the instant of arcing contact separation, the arc durations when interrupting large currents, could be reduced to one-quarter cycle. In such cases it was difficult for observers to distinguish between the character of breaker disturbance when opening on a heavy short or on a dead line.

It is well known that the formation of an arc in a liquid requires first the disintegration of such liquid into its elemental gases. During the subsequent period of arc maintenance, the developed energy must be absorbed by the surrounding medium—a part of this energy causing the continued cracking or disintegration of the oil. During the period of gas development the breaker is subjected to transient hydrostatic pressure waves, dependent upon rate of gas generation and escapes, as well as to somewhat more sustained pressure resulting from gas accumulation and possible ignition in the air space. By reducing the rate of arc energy development, the hydrostatic pressure was decreased and by selectively venting the air space gases in advance of the arc gases, the sustained and ignition pressures were practically eliminated. In the conventional type of dead tank breaker, it is possible to utilize the movement of oil head above the arc gases as a piston to eject the cushioning air space gases. By directing these gases into a suitable separating chamber, it is possible to relieve the breaker rapidly of gas accumulation while preventing an escape of oil and simultaneously permitting cooling of the arc gases below the ignition temperature.

The development of information on other, though less important characteristics may be mentioned such as the effect of catalysts on lowering the ignition temperature of arc gases, variation of arc duration with oil viscosity and the volume of gas generated per kw.-sec. of arc energy for different oils. Such information in conjunction with a better conception of the mechanism of arc rupture not only has contributed to the successful conclusion of these high-current tests but offers a basis for the scientific development of circuit breaker structures of all ratings.

J. D. Hilliard: Mr. B. G. Jamieson in his discussion of the oil circuit breaker papers brings out the importance of the duty cycle in the rating of oil circuit breakers and also the importance of the method of making the tests to determine such rating. Neither of these points has heretofore been discussed to the extent that their importance merits. As a general proposition, all tests of oil circuit breakers should be made under as nearly as possible the identical conditions the breakers are to be subjected to in service. If the breaker is to close under a condition of existing short circuit, then by all means it should be tested under that condition. If the breaker is to be installed where it will have to close and open a short circuit close to the bus bars (zero power factor) then it should be tested under that condition.

If the breaker is to be installed on a system with the neutral either grounded solidly, grounded through a resistance, or ungrounded, then it should be tested under such conditions and in addition *with* and *without* a ground at the point of breakdown. It should be tested with the same operating mechanism which is to operate it in service. If the breaker tested under a particular set of conditions is found to have a certain interrupting capacity, do not assume that under all other conditions it will have the same interrupting capacity because you will be deceiving yourself. If you have made a few shots under a certain set of conditions, you cannot assume that the tests, if continued, will uniformly give the same results. The plot of a set of observations made upon the ordinary oil circuit breaker from low currents up to its maximum rating but under otherwise identical conditions looks like the shot gun pattern of a cylinder bore gun or blunderbus. Certifying to bull's-eyes from such a target is a difficult proposition and besides it is not the bull's-eyes you are after, but the scattered shots on the fringe of the pattern because they represent the spots of maximum gas formation in the breaker and therefore the maximum stresses on the breaker structure.

The foregoing indicates the difficulty of giving an interrupting capacity rating to the ordinary oil circuit breaker. The only absolutely safe thing to do is to specify the rating under the worst possible condition which may exist. It must be expected, however, when such ratings are demanded that the costs will correspond, because the costs of the breaker under the different standards of rating do not change.

Mr. Jamieson draws attention to my italicized statement in the paper. That italicized statement is of considerable importance and was made with a fairly good idea of what the results would have been if conditions had been different; conditions which might easily exist in actual operation of the system, and which might give results much more severe than those observed.

The differential rating of oil circuit breakers operating at 25 and 60 cycles is a debatable question at least to the extent of the ratio of the two frequencies. The time-ampere curve at any frequency is at first ascending, reaches a maximum and then descends with the continual increase of current. The effect noted is due to the inherent blowout effect of the breaker as ordinarily constructed and the fact that several half cycles are required before interruption, the number gradually decreasing with the increase of current is a definite proof that *time*, not half cycles, is the limitation and that the *time* at 60 cycles would be substantially the same as at 25. With the increase of current to a value where one full half cycle is the limit at 25 cycles, then a further increase of current should correspondingly decrease the actual time duration of arc at 60 cycles to less than at 25 cycles, but the magnitude of current required would be such as could be obtained from few generating systems and with an increase of the voltage of the system one would expect the current necessary to interrupt in one-half period to correspondingly increase and it might well be that the actual time limitation would be the break distance between moving and stationary contacts instead of the electro-magnetic blowout effect of the current to be interrupted because the ultimate interruption depends upon the dielectric strength of the medium between the separated electrodes.

The recovery voltage at interruption, together with the phase relation between current and voltage, undoubtedly largely determine the interrupting capacity of the breaker and a study of these recovery voltages under different conditions of operation supply an explanation of many hitherto puzzling phenomena in connection with oil circuit breaker operation. Mr. Meyer notes that most all tests are made either on Sundays or nights after the peak load is over and suspects that the results of tests under these conditions might be different than if they were made under more normal operation conditions. I agree with Mr. Meyer in this belief and think that more tests should be made under normal conditions.

Mr. Wallau's testing experience at Cleveland is not unusual. Certain well recognized factors contributed to the results obtained, and with these factors reversed, the results would have been reversed. It is one more case showing the necessity of making the test conditions the same as the operating conditions.

The General Electric Company did not test any breakers at Baltimore, other than the H-3 and H-6 breakers and the improvements thereon, principally the improvements, because the end sought was to obtain a breaker which would stand repeated short circuits, and this boiled down to obtaining ones which would not throw oil because the inherent interrupting capacity of the old breakers was found to be ample, but the oil throwing property was well known and acknowledged by all. The development was successful and the remodeled breakers are installed in the same cells as the older oil throwing type.

J. B. MacNeill: I wish to state the position of the manufacturers in publishing data on these tests. There had been a feeling that these tests were of a more or less confidential nature, the same as factory tests would be on other lines of apparatus except that when powers such as here used, are employed, factory tests cannot be considered. The feeling was expressed by several operating companies that a large number of new stations were to be built in the near future and that data should be published which would allow the operators to select adequate circuit breakers for such new developments. It is not proper to judge obsolete circuit breakers in many cases by results obtained in Baltimore as these tests were made under the hardest possible conditions obtainable so far as circuit breaker performance is concerned.

Mr. Bang gave in his discussion some of these conditions and he speaks from a full knowledge of this subject as he has done experimental work along these lines.

Mr. Jamieson calls attention to the difference of opinion regarding the duty caused by closing the breaker on the short circuit. The writer did not intend to convey the idea that closing on the short circuit was a negligible matter, but with the type of breaker he was discussing, it seems that the duty of closing on short circuit is relatively light to the duty of opening on short circuit. It is appreciated that the duty of closing of short circuit may differ widely with different breaker constructions.

In connection with Mr. Jamieson's remarks on the duty cycle it should be pointed out that the manufacturers are willing to rate their apparatus on any duty cycle to which the operators as a whole will agree.

Undoubtedly the ratings on duty cycles which involve closing against heavy short circuits will be lower than if the duty involved merely opening the short circuit.

The Electric Power Club has indicated that the ratings of breakers to close against and open short circuits with the more stringent specifications regarding the condition of breaker after test referred to by Mr. Jamieson, will be approximately the same as the ratings which have been given in the past on the so called "two-shot" duty cycle in which the breaker opened the first short circuit and was closed against and opened the second short circuit. This means approximately a de-rating of 20 per cent from present values.

Regarding Mr. Jamieson's comments on repeated closing of heavy short circuits we agree that it is undesirable from an operating point of view to subject systems to repeated shocks. The "five-shot" specifications insisted on by Baltimore Companies was made in view of their experience that imperfections of construction can be disclosed by such a test and that the removal of these imperfections results in superior breakers for any duty cycle; thus, a breaker which will open 20,000 amperes satisfactory 5 times or as was the case in one of the breaker tests, 12 times, undoubtedly has a large factor of safety over 20,000 amperes for less severe duty cycles.

Mr. Meyer refers to tests made by his company on the same general form of breaker covered by the writer in his paper. These tests were of power magnitude comparable with the Baltimore tests and differed principally in that they were not the repeated openings of the short circuits without inspection of the contacts or oil.

The Detroit tests remain to the present time the most important tests that have been made on 24,000-volt circuits.

Mr. A. F. Bang's discussion should be of great interest to operating men, especially as Mr. Bang discusses the possibility of retaining in service by proper system connections, breakers which otherwise would not be serviceable.

The discussion of Mr. O. H. Eshholz is important as he deals with some of the theoretical factors regarding important improvements in construction which were first made possible and later proved out by the Baltimore tests. These tests have allowed us for the first time to study in detail at high powers the exact action of the circuit breakers on short circuit with the aid of complete facilities for analysis. The two operating companies participating in this test, the Pennsylvania Water and Power Company and Consolidated Gas, Electric Light and Power Company of Baltimore have been very patient in allowing the revision of circuit breaker constructions during the course of the tests, and subsequent proving out of alterations. By this method, important results have been secured and it is possible to speak with authority of many features of breaker construction that otherwise would still be in a speculative stage.

Designers of circuit breakers therefore now have a solid foundation of fundamentals to work on so that better distribution of material in designing is possible and increasing rupturing capacity can be had from a given amount of material.

Transmission Line Relay Protection-II

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Review of the Subject.—*This paper is divided into three parts, the first part consisting of a list of relay nomenclature according to function and application, the second part being a general discussion on relay protection with special reference to an investigation of the Protective Devices Committee to obtain information on transmission line protective scheme and the third part, an illustrated description of the results of the investigation.*

The thoroughly proved methods have been given scant consideration but the operating results of new schemes have been treated in brief detail with a statement of the condition which led to the adoption of the various schemes. Many of these schemes require the use of special apparatus which is not obtainable in the open market, though in most cases it was possible to use standard apparatus. It is quite probable that some of these special schemes will be adopted by the leading manufacturers with more or less modification.

In the majority of the cases cited, the actual operating results showing the number of correct and incorrect relay operations have been given and it is probable that this is the first time that such a disclosure has been so generously and frankly made.

Standard names for relays as to function and application as well as qualifying terms which always have the same meaning are very desirable. The number of types of relays now in common use are so great that considerable confusion has resulted from a previous lack of uniformity of identifying designations. This confusion will be eliminated if the manufacturers and users of relays employ the terms given in the paper, which have been approved by the Standards Committee of the Institute.

The first paper of a series contemplated by the Protective Devices Committee was presented three years ago. This is the second paper. Both of these deal with transmission line relay protection, and the Committee now plans to broaden its work to include also relays for protection of apparatus with the expectation of presenting additional data before the Institute as the art progresses.

The entire basis of the present paper is the experience of operating companies as reported by their engineers. The general theory of relays has been almost completely disregarded.

The use of combination over-current and directional schemes has become common due to the very satisfactory results that have been obtained with these relays.

Differential current schemes for parallel lines are increasing in popularity on account of their freedom from a-c. potential connections. Their use is limited, however; the differential power method using directional relays is suitable in those cases where the simpler current balance is not. The tendency appears to be in favor of balancing parallel feeders wherever possible to secure freedom from faulty operation on through faults together with quick action in case of trouble on one of the group. A number of different schemes, based generally on the same principle, is described in considerable detail.

The split conductor protection, though apparently successful, does not seem to be extending greatly beyond the early installations in this country, principally on account of the high cost of the cable.

Pilot wire protection, while abandoned by some operators, is being tried out in newer forms by others with some apparent likelihood of future extension.

The use of ground relays has been considerably extended particularly on systems having neutrals grounded through a comparatively high resistance. The application of these ground relays with regard to current and time settings is based on the same principles that apply for the relays connected in the phase. Both over-current and directional relays have been used with apparently successful results. By energizing only in case of accidental ground these relays may be set for much lower current values than the phase relays and in some cases at lower time values. The ground relays may be connected to sheath transformers or in the residual circuit of three current transformers of the usual type. Several applications of ground relays with pilot wire connections have been reported.

A very sensitive potential ground relay scheme for the protection of comparatively isolated circuits has been operating with good results for a number of years.

In one case, in order to avoid the necessity of installing grounding transformers, provision has been made to ground a second phase of the bus when it is shown by potential ground relays that an accidental ground has occurred on one phase. In this way a phase short circuit is produced permitting the faulty section to be isolated by standard over-current and directional relays.

An application of the combination of under-voltage and over-current relays is described. It takes into consideration the feature that the potential would be reduced proportionately as the faults is approached which adds a further degree of selectivity to the ordinary current method.

Accurate calculation of short circuit currents has proved highly desirable and considerable data concerning mathematical and mechanical methods of making these calculations are described.

General principles of relay application and practise concerning relay settings are discussed. Some notes are included relative to foreign practise and some of the outstanding features of installations in use in other countries have been described.

IN the paper on Transmission Line Relay Protection which was presented before the Institute in June 1919 there was included a proposed Relay Nomenclature. This with slight modifications was adopted by the Standards Committee on May 19, 1921. The approved nomenclature is as follows:

Classification According to Functions

Where relays operate in response to changes in more than one condition, all functions should be mentioned.

Electric Protective Relay. An electric protective relay is an intermediate device, equipped with contacts to open or close an auxiliary circuit, by means of which one circuit is indirectly controlled by a change in conditions in the same or other circuits.

Directional Relay. A directional relay is one which functions in conformance with direction of power, or voltage, or current, or phase rotation, etc.

Power-Directional Relay. A power-directional relay is one which functions in conformance with direction of power.

Note: This includes both uni-directional relays with single-throw contacts and duo-directional relays with double-throw contacts. The reason this name is preferred to "reverse power" is that the device is frequently used to

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function under normal direction of power. Furthermore, in some cases the normal condition of the system may permit power to flow in either direction. Relays for use in either alternating- or direct-current circuits are to be classed as power-directional relays.

Polarity-Directional Relay. A polarity-directional relay is one which functions by reason of a change in the direction of polarity.

Phase-Rotation Relay. A phase-rotation relay is one which functions by reason of a change in direction of phase rotation.

Current Relay. A current relay is one which functions at a predetermined value of the current. These may be either over-current relays or under-current relays.

Voltage Relay. A voltage relay is one which functions at a predetermined value of the voltage. These may be either over-voltage relays or under-voltage relays.

Power Relay. A power relay is one which functions at a predetermined value of watts. These may be either over-power relays or under-power relays.

Frequency Relay. A frequency relay is one which functions at a predetermined value of frequency. These may be either over-frequency relays or under-frequency relays.

Temperature Relay. A temperature relay is one which functions at a predetermined temperature in the apparatus protected.

Open-Phase Relay. An open-phase relay is one which functions by reason of the opening of one phase of a polyphase circuit.

Differential Relay. A differential relay is one which functions by reason of the difference between two quantities such as current, or voltage, etc.

Note: This term includes relays heretofore known as "ratio balance relays," "biased," and "percentage differential relays."

Classification According to Application

Locking Relay. A locking relay is one which renders some other relay or other device inoperative under predetermined values of current, or voltage, etc.

Trip-Free Relay. A trip-free relay is one which prevents holding in an electrically operated device such as a circuit-breaker while an abnormal condition exists on the circuit.

Auxiliary Relay. An auxiliary relay is one which assists another relay in the performance of its function and which operates in response to the opening or closing of its operating circuit.

Signal Relay. A signal relay is an auxiliary relay which operates an audible or visible signal.

General Qualifying Terms

Inverse Time. Inverse time is a qualifying term applied to any relay indicating that there is purposely introduced a delayed action, which delay decreases as the operating force increases.

Definite Time. Definite time is a qualifying term applied to any relay indicating that there is purposely introduced a delayed action, which delay remains substantially constant regardless of the magnitude of the operating force. (For forces slightly above the minimum operating value the delay may be inverse.)

Instantaneous. Instantaneous is a qualifying term applied to any relay indicating that no delayed action is purposely introduced.

Notching. Notching is a qualifying term applied to any relay indicating that a number of separate impulses are required to complete operation.

In addition to the standardized nomenclature, used throughout this paper, it was found desirable to adopt uniform terms for use in describing devices and characteristics of devices and systems which have heretofore been known by more than one name.

In order that there may be no misunderstanding as to use of these terms the following definitions are given:

Differential Relay. Explanatory note. In a differential relay the resultant force operating the relay, may be obtained by mechanical, magnetic or electrical means. Thus a relay is described as a mechnical differential relay, a magnetic differential relay or an electrical differential relay.

Percentage Differential. Percentage differential is a term descriptive of the operating characteristics of one class of differential relay and indicates that the relay requires an increasing difference to cause operation, which difference will approach a definite percentage of either or both of the opposing quantities.

Pick-up Value. The pick-up value, expressed in current, voltage, etc., is the minimum value at which the relay will complete its function.

Drop-Out Value. The drop-out value, expressed in current, voltage, etc. is the maximum value at which the relay starts to rest.

Balanced and Residual Currents. The currents in the several wires of a circuit are divided for convenience into two classes of components, "balanced" and "residual."

The "balanced currents" are those wholly confined to the wires of the circuit. Hence, their algebraic sum is zero at every instant.

The remaining components of the currents in the several wires which exist under conditions other than perfect balance, are termed "residual." The sum of the residual components is the "residual current" of the circuit. It is equivalent to a single-phase current in a circuit having the wires in multiple as one side, and the ground as the other.

Mathematically expressed, the residual current is the vector sum of the currents in the several wires, while the balance currents are those components whose vector sum is zero.

Introduction

As the quality of the service rendered by central stations becomes better the standard of service demanded by the public becomes higher. The only way of meeting this demand is by constantly improving protective devices and their application so that a fault in the system will be confined to the smallest possible area with the least possible disturbance to the healthy sections of the system.

It was in the hope of seeing such results realized that the Protective Devices Committee, several years ago, began a systematic study of the problem of protection. As a result, a Paper on Transmission Line Relay Protection was presented to the Institute in June 1919, being the first of a proposed series, covering the investigations of the Committee. In this first paper were incorporated a recommendation on standard relay nomenclature, a statement of the methods followed in approved relay practise and descriptions of such schemes as were considered as standard at that time because of successful operation.

No attempt was made to describe the many special schemes then on trial but early in 1920 a request was sent out to a number of operating companies, asking for information on transmission line relay schemes, which were being, or had been, tried out and proved successful or abandoned as worthless. This particular method was adopted as the most efficient means of adding to the data on hand as presented in the previous paper, and of getting an accurate idea of the latest developments as well as an idea of the general tendency in the art of relay protection.

The Relay Subcommittee of the Protective Devices Committee, has as its function the keeping of an authentic record of the development and operation of various protective relay schemes. It is hoped that by presenting before the Institute, from time to time, such important data as may be gathered, duplication of effort among engineers may be avoided and the standardization of protective relays and schemes, fostered. Most of the central station companies, to whom the request for information was sent, manifested an interest and a desire for cooperation by replying promptly. Replies from others came in more slowly and it is only within the last few months that all the replies were received. On account of this the information given in some of the earlier replies was more or less out of date by the time the last ones came in. Therefore, when the work of compiling the data and coordinating it into the form of a paper was begun, the Committee where necessary asked for additional data on such schemes as it was thought desirable to include in the paper. Request was also made for data on any schemes planned or installed subsequent to the original inquiry. It is, therefore, believed that data contained in this paper are complete up to within a few months of the present date. There are probably some schemes with which the committee was not acquainted and it is possible that some companies may have operating data, besides those given, on schemes which are described.

In the previous paper an attempt was made to emphasize the desirability of setting relays for short-circuit current values, rather than on the basis of load current as was once common practise. Since that time important developments in methods of determining short-circuit current values have been made and it was thought fitting to give, in this paper, a description of the various methods used. Both the mechanical and mathematical methods are discussed with the advantages and limitations of each, and consideration is given to the factors which must be taken into account in making the determination.

Following this it also seemed advisable to add some observations on the best practise in making relay current and time settings as well as on the factors to be considered in making such settings. A few notes are also made regarding foreign practise with comparisons to American practise, where possible.

The recommendation on relay nomenclature made by the Protective Devices Committee in 1919, has been approved, with slight modifications by the Standards Committee and is now finding its way into general use. Having taken this step in the direction of standardization there now appears to be a need for some form of standard symbols for representing various types of protective relays in schematic, single-line and detail diagrams. In going over the diagrams submitted to the Committee, such a great diversity of symbols was found that it was sometimes difficult to understand the schemes and to determine their relation to other schemes. It is believed that a convenient standard symbol can be devised to represent each type of relay, thus eliminating a great deal of confusion and making all diagrams easily readable. It is the intention of the Committee to devote some time to this problem in the near future.

In addition to the difficulty experienced on account of the many symbols used, there was also some trouble in classifying various schemes because of great variety of names used in describing them. In order that such confusion may be avoided in presenting these schemes the Committee has divided them into five main classifications as follows:

1. Schemes using over-current and directional relays in combination.
2. Differential current schemes
3. Differential power schemes
4. Ground relay schemes
5. Schemes using over-current and under-voltage relays in combination.

All the schemes submitted may be placed in one or the other of these classifications. The subdivisions, however, were found to be more difficult and while the Committee has grouped the schemes in what seems to be the most logical manner, it is not intended that the designations used shall be taken as recommendations. It is believed, however, that the standardization of terms used in describing schemes would be very advantageous and it is hoped to make this the subject of a future study by the Committee.

The investigations by the Committee, as covered in both the previous and present papers have been confined altogether to transmission line relay protection. Some study has been made, from time to time, on apparatus protection but this was usually the result of an inquiry on some specific problem and the information was given out in the form of a letter.

It is intended, therefore, next to undertake to collect and coordinate data on the protection of apparatus and on special relay devices and schemes such as are used in remote-controlled and automatic stations. Such data will be presented to the Institute in the form of papers.

In replying to the request for information practically every central station company gave a description of all relay schemes which it has used, both standardized and otherwise. Some schemes which were considered as tried and proved by some companies were described as trial installations by others. It will, therefore, be found that some of the schemes described in this paper as being on trial, may be considered standard by some engineers. It was thought best, however, to include all schemes reported as being on trial and at least one is described which was discussed in the previous paper.

In comparing these last replies to those received several years ago there was found to be a noticeable increase in the use of the schemes described in the previous paper. It was also apparent that a greater number of companies were using the approved methods of setting and testing relays. Almost every company reported that good results were being obtained with such schemes and not a few reported that older schemes and types of relays which were not giving good results were being replaced by more recent schemes using modern types of relays.

That there is considerable activity in the experimental field is shown by the number of new schemes now on trial. With the increasing size and complexity of the modern power system and with the varied conditions of operation introduced by interconnection and concentration of tremendous amounts of energy in small areas, new problems are constantly arising and new schemes must be devised to take care of the requirements. It is quite noticeable that, where possible, tried and proved schemes are being used but when these fail new ones are devised and tried out. Such schemes usually require a period of a year or more to determine whether they are effective and in the three years since the previous paper a considerable number of schemes have been brought out to take care of conditions not so pertinent at that time. The number of schemes and the record of their operation have been sufficient to determine in a general way the tendency in principle and design of protective relay schemes. As can be seen from the descriptions given later, the trend in development is toward the selection of defective lines by the use of differential schemes operating on the fault or trouble current rather than by relying altogether on the use of progressive time settings and current settings made on the basis of the line current. This is the natural result of the increase in the size of systems as to capacity, area covered, and number of stations operated in parallel. Beyond a certain point progressive time settings necessitate maximum time intervals which are so high as to become impractical, especially where sensitive synchronous apparatus is involved. The need for schemes which do not require progressive time settings and which will disconnect the faulty section with the least possible delay, has thus become imperative. Therefore, the greatest development seems to be in the use of the differential current and differential power principles in which the defective line is disconnected instantaneously and in which the equipment on one section is not affected by trouble in another section. The success with which such schemes are being used gives proof of the soundness of the principle and holds promise of even better results in the future.

Considerable attention has been given to the problem of disconnecting grounded feeders. This problem has become especially important because of the more general practise of grounding of systems, particularly where a comparatively high ground resistance is used, resulting in ground currents which may be less than full load value. This has made it necessary to devise schemes which will disconnect the grounded line before the trouble develops into a phase-to-phase short circuit. Especially is this necessary on overhead lines in order to prevent the trouble from spreading to adjacent circuits.

Another problem, which has resulted in the development of a very effective scheme, is that of detecting and disconnecting a grounded feeder on systems having an ungrounded neutral. In a great many instances it is found impractical to ground a delta system and this development offers a comparatively simple and inexpensive solution to the problem of grounds which might later develop into cross short circuits ordinarily resulting in serious interruptions.

Some schemes which are reported as trial installations are only modifications of schemes which were described as standard in the previous paper and in most cases these modifications were made to take care of some special condition. In describing the schemes an attempt has been made in each case to give the reason or special condition which prompted its development and application, the principle of operation, a description of the apparatus used, a summary of its operating results and its advantages and disadvantages.

The request for information was sent to about sixty operating companies in all parts of this country and Canada and in response thirty-five more or less complete replies were received. Of these reporting companies, thirteen have systems supplying city loads exclusively and twenty-two have either long distance transmission systems or have an extensive high-voltage network. This paper is the result of a careful analysis of the data submitted in the replies and schemes described are representative of the best American practise.

Description of Relay Schemes for the Protection of Transmission Lines

I. Over-current and Directional Schemes.

The use of over-current relays, either alone or in combination with directional relays, to obtain protection strictly on the basis of current intensity, time and direction is too well known to warrant repetition. However, two of the more unusual modifications are given.

Inverse Time Over-Current and Directional Relays

One of the large power companies having a system comprised in part of approximately eight sections in ring formation, together with a number of interconnecting circuits into which power is fed at six principal points, has found that in order to secure selective action under various operating conditions a very inverse time characteristic was required for the over-current relays. The ordinary method of time grading was not considered satisfactory because with changing generating conditions and the frequent opening of some circuit the general power distribution was sufficiently disturbed to alter the order of the time grading required. Due to the number of lines involved, however, at most of the stations it was found that the circuit in trouble would in nearly all cases carry a materially greater current than any other contributing circuit. Use of an inverse time characteristic which continued to give the necessary degree of selectivity for this natural difference in current over the complete range of probable faults was finally adopted.

In some cases definite minimum time was also required and at one point a rather high definite time was provided for very low current values, changing later into the inverse time. This unusual characteristic was required in order to permit operation at comparatively low current values as these would be limited due to the very long time involved if the fault were at the far end, whereas, for a short circuit close to the circuit breaker in question, the current would be of such large proportions that delay in tripping would be dangerous besides placing in jeopardy the other contributing lines. It was this latter consideration that required the inverse portion.

The directional relays were of standard types applied in accordance with usual practise.

The Use of Automatic Bus Sectionalizing to Reduce the Duty on Oil Circuit Breakers

In at least one case it was reported that the system had grown to such proportions that, in order to use circuit breakers then installed, it was decided to automatically sectionalize the buses in some stations and thereby limit the current to be interrupted in case of a fault. In such schemes no special relays are necessary, the standard over-current directional combination generally being used. General practise, however, seems to require that, wherever possible, circuit breakers shall be capable of interrupting the maximum power which may flow through them in case of a fault.

II. Differential Current Schemes. The balancing of parallel groups so as to provide sensitivity for faults within the group and, at the same time, safeguard against action for all other faults appears very successful. Its popularity is still further increased, whenever conditions permit, by the elimination of all alternating current potential connections as is done in the various differential current schemes reported.

Differential Current Protection for Two Lines

One company uses a differential current relay scheme which is interesting because it is an elementary form of a more complete scheme, operating on the same principle, and described elsewhere.

The application is made to paired 60-kv., 4/0 lines, 175 miles long, forming a bus for a complete transmission system. These lines are connected to power plants at five different points with a total generating capacity of 161,000 kw. Previous to the installation of these relays the transmission system was operated so that each substation was supplied from only one source of energy as attempts to operate the lines in parallel had resulted, in some cases in serious interruptions to service due to the splitting up of the system.

For proper functioning of the relay system more current must flow in the faulty line than in the healthy line. The differential current relay consists of two similar solenoids with movable cores suspended on an arm pivoted at the middle point. Two sets of contacts are mounted in such a manner that the throw of the arm in either direction, due to excess current in one solenoid, will close a contact. One solenoid of a differential current relay and one induction type over-current relay are connected in series with a current transformer. Each set of contacts on the differential relay is connected in series with the contacts of a corresponding over-current relay. The contacts of the over-current relays, however, are normally short-circuited by a pallet switches in the circuit breakers when the breakers are closed. Thus the differential relay will discriminate between lines in case of a short circuit or ground involving only one line. When the faulty line is cleared, the opening of the circuit breakers on this line removes the short circuit on the contacts of the over-current relays, and the differential relay, having only one solenoid excited, closes the contacts to complete the tripping circuit. Thus, over-current protection is automatically cut into service on the remaining line when one line is out of service.

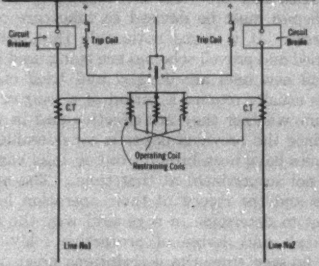

Fig. 1—Selective Differential Relay Scheme for Two Parallel Lines

Satisfactory operations have resulted from the use of the differential current relay in cases of trouble which it was desired to clear.

The principal advantages of this scheme are the elimination of potential transformers and time settings. It also permits the isolation of the fault in the minimum time.

The disadvantages appear to be the extreme sensitivity under balanced condition which may result in faulty operations. There is also the necessity of providing additional protection for bus or substation troubles if such protection is desired.

This relay scheme will only function properly where an unbalance of currents is assured under all faulty conditions.

Selective Differential Relay Schemes

The relay illustrated in Fig. 1 operates to trip that one of a pair of parallel lines which carries the greater current in case the pair becomes unbalanced due to a fault. The relay in most cases requires an unbalance of at least normal load and for higher currents this unbalance must exceed some percentage of the smaller of the two currents. This is generally in the neighborhood of 25 per cent, thereby automatically compensating for normal unbalancing, such as may be present when slightly different lengths of line are involved, or a difference such as is occasioned by mutual inductance of overhead lines which frequently has a varying effect at times of faults of different characters. This percentage of unbalance is also capable of adjustment in order to further compensate for any known differences in characteristics of the lines involved, it not being necessary to maintain the same slope on both sides.

As mentioned above, this relay operates to open the circuit breaker of the line carrying the greater current. Therefore, it is perhaps always applicable to outgoing parallel circuits which are sufficiently balanced under normal conditions but should never be used on incoming lines where the line in trouble will not carry the greater current as, for instance, would be the case for a substation supplied by no other source of power. This would require that the good line supply whatever current might be taken by the connecting substation load as well as the fault, and would result in tripping the wrong breaker.

The relays consist of three coils whose plungers are attached to a balance arm on which the contacts are mounted. Current through the two end coils tends to hold down their plungers. The center coil is differentially connected or wound and with a current of equal value in the two windings no force is exerted on the plungers. The plunger of this coil has an adjustment for pick up value. When a fault occurs on one line, the force in one end coil and in the middle coil increases, so that the one end coil holds down that end of the arm while the middle coil raises its plunger and pivots the arm about the end coil, thus making contact in the proper direction to trip out the defective line.

The one company reporting the greatest experience, under actual operating conditions, with this type of relay installs them in some instances on incoming lines to buses which are supplied with abundance of other power, thus accounting for the good record reported.

This same company has in some cases four and six parallel lines between stations protected in this way, the lines being grouped in two or three pairs, each pair arranged as indicated in Fig. 1. Any odd lines are provided with time over-current protection having a comparatively low time setting. This appears to have no particular disadvantage where other contributing lines are generally balanced because of the instantaneous action on the balanced groups and the safeguarding against operation of the balanced groups for any fault which might occur in one of these odd circuits. Time over-current protection is automatically provided when one circuit of the balanced group is out of service.

There are 34 of these installations protecting 17 pairs of lines, some underground and some overhead and some combinations of underground and overhead. These circuits which have been in service for about 2½ years have been subjected to 37 faults, all of which have been cleared correctly without affecting other lines. On the other hand, 900 additional relay operations were reported on other contributing lines, involving a total of 1500 miles of circuits, in no case of which did these selective differential relays operate incorrectly. On that part of the system not protected in this way this company reports 85 per cent correct operation, counting doubtful operations in general as being incorrect.

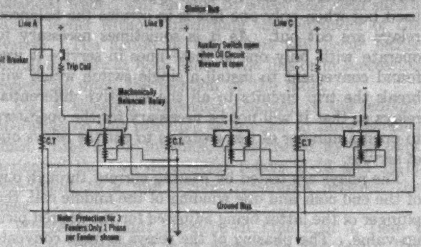
Station Bus
Line A
Line B
Line C
ircuit Breaker
Trip Coil
Auxiliary Switch open when Oil Circuit Breaker is open
+
-
Mechanically Balanced Relay
C.T
C.T.
C.T
Ground Bus
Note: Protection for 3 Feeders Only 1 Phase per Feeder shown

FIG. 2—SCHEMATIC DIAGRAM OF SELECTIVE DIFFERENTIAL RELAY SCHEME

A second company has very recently installed equipment similar to that shown in Fig. 1, except that it is modified to include a fourth similar relay, connected in the same manner, to the neutral lead of the current transformers to operate more sensitively in case of grounds. No operating data are yet available.

The third company, reporting the use of these relays, made no particular comment regarding their operation. The general statement that all relays on the system operated 90 per cent correctly does not give any clear indication of the success of this particular installation.

This same general method of protection has also been extended in the case of one company to the protection of three lines in parallel as illustrated in Fig. 2. It will be noted that in this case each line is balanced with each of the other two lines so that in order to disconnect one breaker it must carry a greater current than either of the two companion lines. This is insured by the tripping contact connections which are made so that both relays connected to the line in trouble must operate before its breaker can be tripped. It will be observed that this furnishes an additional slight advantage over the simple two-line group although the extra relays and connections are in most cases considered unnecessary.

The three open-wire lines, on which this scheme is used, were installed to operate in parallel with four split-conductor cables between a generating station and an important substation, and protection for the open-wire lines, comparable to that afforded the cables, was desired. It may be mentioned, as a matter of interest, that in order to parallel these open-wire lines and split-conductor cables, special precautions had to be taken on account of the large difference in reactance. By using external reactance it was possible to adjust them so that the characteristics were approximately the same, thus making parallel operation practical.

These three circuits also have over-current relays to clear bus short circuits and to give protection when only one or two lines are in service. When two or three lines are in service both types of protection are used but when only one line is in service the balanced relays are cut out. As it is sometimes necessary to operate with only one of these lines in service it was found convenient to install a single switch which will break the trip circuits to all the selective differential relays so that it will not be necessary for the operators to open a number of test switches to cut the relays out of service.

The relays are tested by passing current through one of the end coils and one winding of the middle coil, the plunger of the latter being adjusted for the desired pick up value. The phasing of the relays is most conveniently checked with a four quadrant power factor meter as described on page 851 of the A. I. E. E. TRANSACTIONS for 1919.

These installations have been in service since August 1919, and while there has been only one operation this was a correct one. A pothead failed and the defective line was cleared successfully without taking any other line with it.

Insofar as this particular company is concerned no tests have been made to duplicate operating conditions and as there has been but one case of trouble since the installation, the evidence is not considered sufficient to form conclusions regarding the selectivity of the scheme when called upon to isolate the faulty line of the three, nor is there sufficient data to indicate any advantages or disadvantages in operating characteristics. It is, however, considered to have the following inherent characteristics:

1. Instantaneous selectivity.
2. Freedom from potential transformer connections.
3. It has a percentage differential action which automatically compensates for normal unbalancing.
4. It does not afford protection against bus short circuits, requiring additional relays if such protection is desired.
5. Protection is not given when only one line is in service, requiring additional relays if such protection is desired.
6. It cannot be applied at the substation end of duplicate lines where there is no additional source of power at the substation end, as in such a case the fault currents in the two lines will be equal.
7. It is somewhat complicated and expensive in wiring when used on more than three lines.

No changes are contemplated to improve the installation though it will be retained until more data are obtained. It is believed that the failure of the relays to operate on numerous though short circuits indicates that they are satisfactory in this respect.

Selective Differential Scheme Using Induction-Type Relay

Another company reports that it has already completed the trial of a selective differential scheme which it now considers thoroughly proved. It differs in principle from the foregoing in that induction type relays are used, although it is applied to duplicate lines in practically the same manner.

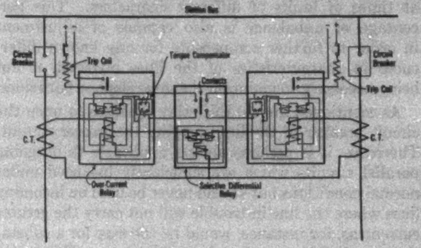

FIG. 3—SELECTIVE DIFFERENTIAL SCHEME USING INDUCTION-TYPE RELAY

Referring to Fig. 3, the scheme makes use of one differential relay connected between the two lines with an over-current relay in each line, so that the system will be sectionalized even if trouble should occur on the station bus. This also makes each line automatic after its companion line has been cut out of service. It will be observed that the differential relay does not directly trip the circuit breaker, but is arranged to decrease the time setting of the proper over-current relay, thus allowing this latter relay to trip out its circuit breaker. The over-current relay is of that induction type which is equipped with the so-called "torque compensator" for the purpose of giving it a definite time of operation. This "torque compensator" is short-circuited by the operation of the differential relay, thus allowing the over-current relay to operate very quickly. When one line is out of service, the differential relay is disconnected and the over-current relay will operate in the time for which it is set.

There are about thirteen pairs of lines protected on both ends by these relays, some of which have been in service for three years. There have been about 50 correct operations and no interruptions to service due to incorrect operations, although one pair of lines which are not duplicates, and therefore not balanced, have tripped out several times on through short circuits. Improvements are now being made which are expected to overcome this difficulty.

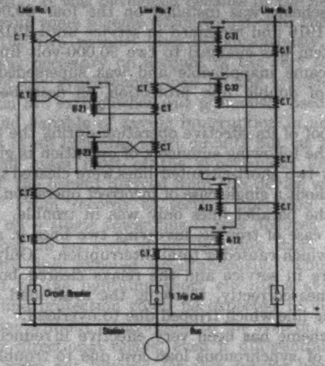

FIG. 4—SCHEMATIC DIAGRAM OF DIFFERENTIAL CURRENT RELAY SYSTEM AS USED ON THREE PARALLEL LINES

This scheme has the advantage of being quick in operation and it does not require the use of potential transformers. It is particularly useful on tie lines between generating stations.

It has the disadvantage, inherent to all differential schemes of a like nature, in that it requires interlocking circuits between the circuit breakers to prevent operation when only one line is in service. It likewise cannot be used on the substation end of duplicate lines unless there is an additional source of power in the substation.

When used on a system which is grounded through a high resistance four relays may be used, three being for the purpose of clearing phase short circuits and the fourth, wound to operate on smaller currents and connected in the neutral wire between the two banks of current transformers, for clearing faults to ground.

Differential Current System for the Protection of Three or More Parallel Lines[1]

One company reports the installation of a differential current system for the protection of three or more parallel lines. It was adopted because of the desirability of selecting and clearing the defective line instantaneously, on account of the extremely sensitive character of the synchronous load on the system. It was installed first on four parallel feeders between a generating station and a substation. These feeders operate at 12,000 volts and are ungrounded, the system being delta connected. Later it was installed on four 60,000-volt lines 80 miles long. This part of the system was also delta connected and ungrounded.

The principle of this system of protection is based upon the fact that the current of a line becomes unbalanced relative to the same phases of other parallel lines when a fault occurs on it, whereas the current in the other parallel lines will remain balanced with respect to each other. This will hold true for a short circuit at any point on a system of three or more parallel lines provided their characteristics are not appreciably different. Therefore, an arrangement of differential relays coupling a feeder with other parallel feeders and having the trip circuits of these relays interconnected in such a way that their joint action will trip the unbalanced feeder, will be able to select and clear such a faulty feeder without disturbing the remainder of the system. The action of the relays will occur either simultaneously at both ends of the line or in succession depending upon the location of the fault.

Fig. 4 shows a schematic diagram of the scheme, operating on this principle as applied to three parallel lines. Line 1, for instance, is protected by the joint action of the two differential relays *A*-12 and *A*-13 responding to a line current difference between the lines.

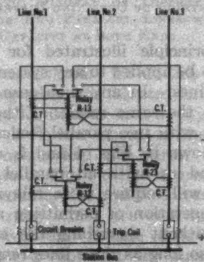

FIG. 5—SCHEMATIC DIAGRAM OF DIFFERENTIAL CURRENT RELAY SYSTEM FOR THREE LINES USING ONE RELAY PER LINE

Whenever a fault develops in Line 2 or 3, Line 1 becomes unbalanced with respect to the faulty line and causes the corresponding relay to trip. Line 1 will remain balanced, however, with the other sound line, and as a result the sound relay will remain open thus preventing Line 1 from being tripped out. Should the fault be on Line 1, it will become unbalanced with respect to Lines 2 and 3, resulting in the action of relays *A*-12 and *A*-13 and tripping out the defective line. In a like manner, relays *B*-23 and *B*-21 provide protection for Line 2 and relays *C*-32 and *C*-31 for Line 3.

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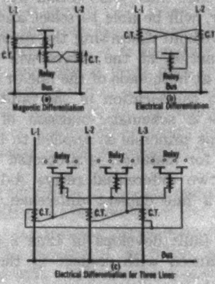
[1] "Relay Protective Features of Toronto Power Company's Transmission and Distribution System" by P. Ackerman. The Engineering Institute of Canada. April 14, 1921.

With the arrangement shown in Fig. 4, six differential relays are required for the protection of a three line system. It will be observed, however, that in the whole combination, two relays each form differential relays for the same two lines, the only difference being that the trip contacts of the two relays are inserted in two different trip circuits. By modifying the system as shown in Fig. 5, the number of relays required may be reduced by one-half. In this, each relay has two independent trip contacts, each contact being inserted in one of the trip circuits of the two lines from which the relay is energized. In actual practise only one current transformer is used for each line. The schematic arrangement showing each relay coil being fed from a separate current transformer, was chosen only to show clearly the relation between the various lines and relays.



(a) Magnetic Differentiation (b) Electrical Differentiation

(c) Electrical Differentiation for Three Lines

FIG. 6—METHODS OF OBTAINING DIFFERENTIATION

The same principle illustrated for the three-line system can also be applied to any system of more than three parallel lines. In any such case two ways are open to secure the same result. Either each feeder can be coupled with two parallel feeders to form the combination shown in Figs. 4 and 5, or each feeder may be coupled up with all parallel feeders. The latter method will require more relays but has the advantage in operation of permitting any line to be disconnected without disturbing the effectiveness of the protection so long as three lines remain in service.

Where two lines only are left in service, the protection will not be affected by through short circuits, but for short circuits within the section both lines are opened without discrimination.

With only one line in service a short circuit at any point on the system may open this line instantaneously.

All the differential relays shown in the foregoing diagram have been of the magnetic differentiation type, that is, relays with two independent current coils and normally bucking each other as shown in Fig. 6, (a). In a similar way electrical differentiation can be employed by connecting the current transformers in series and shunting the relay coil across them as shown in Fig. 6, (b). Fig. 6 (c) shows three-line protection employing electrical differentiation.

This scheme was installed on the four 60,000-volt lines in 1916 and remained in service until 1918 when this system was changed to two 90,000-volt lines. It then became inapplicable and was superseded by a scheme of double line protection, as described elsewhere.

As proof of its effective operation during the time of service the following summary of operation is given:

Thirty-two short-circuited lines were cleared successfully without a single case of incorrect operation, where one of the parallel lines only was in trouble. There was one case of trouble, involving two lines in a short circuit, which caused a total interruption. Only three lines were in service and the relays cleared both the faulty lines correctly, throwing the total load on the remaining line which tripped due to overload.

The scheme has been very effective in reducing the amount of synchronous load lost due to trouble. In twenty-eight out of the thirty-three cases less than 5 per cent of the synchronous load was dropped and in two other cases the loss was less than 10 per cent.

This scheme has also been installed on the 12,000-volt distribution system for all groups of three parallel feeders. The installation was based on the satisfactory results obtained on the 60,000-volt system and was put in with the double object of trying, in case of cable failure, to save the particular substation from total interruption and to obtain instantaneous clearance thus saving the remainder of the system from serious secondary disturbances.

On several occasions since this 12,000-volt installation, cable faults have been cleared successfully without loss of load. In some other cases the relay scheme has been unable to operate properly because of the failure of other apparatus. The less fortunate performance of the 12,000-volt system, therefore, cannot be attributed to the failure of the relays to function properly. The results on the 60,000-volt system are considered sufficient proof of the correctness of the principle and its effectiveness.

The chief disadvantages of this scheme are that it is somewhat complicated as to wiring, especially on more than three lines, and when only two lines are in service it is indiscriminating. Additional relays must also be provided to take care of bus short circuits if such protection is desired and with only one line in operation the differential relay setting must be above full-load current.

It has, however, the advantages of being free from the complications and uncertainty of action inherent to schemes using potential and is less expensive, especially on high-voltage systems.

Differential Current Scheme for the Protection of Two Parallel Lines[2]

One company reported the installation of a differential current system of protection for two parallel lines having generators or synchronous capacity at both ends. It was developed because of the necessity of obtaining some scheme which would clear the faulty one of the two parallel lines instantaneously. Such action was necessary on account of the very sensitive nature of the synchronous load on the system. The Nicholson arc extinguisher was previously used and it was found capable of saving interruption in about 75 per cent of all lightning short circuits but, as in practically all cases most of the synchronous load was dropped, the benefit derived from this device was only partial. From records of section operation of two circuits on a single tower line it was deduced that in only about 25 per cent of all lightning short circuits were both lines affected simultaneously. Thus in 75 per cent of the lightning short circuits a system of double line protection could be expected to clear the faulty line without interruption to the system.

Power directional relays, even if differentially connected, were not favored for this service because of the sluggishness and uncertainty of action on short circuits near the station. The Mertz-Price system was also excluded for practical and commercial reasons because of the length of the line.

A solution was, therefore, sought in a plain current differentiation between the same phases of two parallel lines, taking advantage of that fact that, with synchronous capacity at both ends, a short-circuited line will manifest itself by drawing more current than the good line. This will hold true for a short circuit at any point between stations and a relay actuated by the excess current to trip the faulty line and simultaneously prevent the sound line from tripping, can select and clear the faulty line without affecting the service over the other line.

A schematic diagram of such a relay is given in Fig. 7 (a). The relay consists of two instantaneous elements so interlocked that the contacts of only one can be closed at a time. Short circuits outside the section so protected would act on the two elements with about equal force so that theoretically neither could make contact. In actual practise, however, one would invariably overcome the other and result in an incorrect operation. In order to overcome this difficulty an additional single-coil relay, energized by the differential current between the two lines, is used. This is shown in Fig. 7 (b), and its contacts are connected in series with those of the two-coil differential relays so that only joint action of the two can trip a circuit breaker.

Thus any through short circuit, resulting in an approximately balanced current flow in the two lines, cannot actuate the single-coil differential relay. The trip circuits will, therefore, remain open even if the two-coil differential relay should be moved into one of the two contact positions.

In the case of a fault on one of the two lines, however, there will always be sufficient differential current between lines to actuate the single-coil relay and thus select, jointly with the two-coil differential relay, the faulty line.

With only these two relays there are certain conditions of short circuit under which the sound line would be tripped out immediately after the faulty line had tripped out at one end. It is, therefore, essential that the trip circuit of the sound line be opened before the faulty line has cleared. To do this an electrically controlled locking relay was adopted, energized by the oil circuit-breaker control in such a way that it opens the trip circuit of its line whenever the opposite line circuit breaker opens, and vice versa.

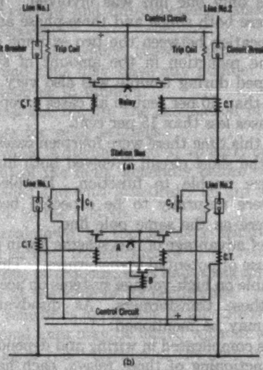


FIG. 7—SCHEMATIC DIAGRAM OF DIFFERENTIAL CURRENT RELAY SYSTEM FOR TWO PARALLEL LINES WITH GENERATOR OR SYNCHRONOUS CAPACITY AT BOTH ENDS

Referring again to Fig. 7 (b), *A* represents the relay which selects the faulty line and *B* represents the single-coil differential relay which prevents incorrect operation of the two-coil relay in case of through short circuits. *C*-1 and *C*-2 represent the automatic locking relays operated by the electrical control of the opposite line circuit breakers to prevent the sound line from opening immediately after the faulty line in case of short circuits at the extreme ends of the section.

Thus all conditions are taken care of and the scheme has proved effective for any kind of line short circuit when only one line was in trouble. It was installed first on two pairs of 60,000-volt lines, 80 miles long, and was operated in conjunction with the differential current scheme for three or more parallel lines, as described elsewhere, until these four lines were changed to two 90,000-volt lines when the other scheme became inapplicable. This method of operation was followed about two years and as long as three or four lines were available the double line protection was used only during lightning storms or whenever other operating conditions arose which left only two lines in service. During lightning storms only two lines were operated as, on account of the insulators, only two were considered lightning safe.

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[2] "Relay Protective Features of Toronto Power Company's Transmission and Distribution System" by P. Ackerman. The Engineering Institute of Canada. April 14, 1921.

Since the change to the 90,000-volt double line system the scheme has been in constant service. Operating records were available only from 1917 through eleven months of 1920, and during this time ninety-seven short circuits were cleared without a single failure, so long as only one line was involved. These short circuits were both single and three-phase and at every possible location between the two extreme ends of the lines. The reduction in the amount of synchronous load dropped during trouble was also very noticeable, being less than 30 per cent in all cases except eight and in most cases less than 15 per cent.

During this time there were fourteen cases of trouble in which the short circuit involved both lines and the relays were unable to function. Double-line short circuits were naturally to be expected because both circuits were on the same pole line.

The chief advantage of this scheme lies in its freedom from the use of potential transformers. This is especially desirable on high-voltage systems on account of the cost of these transformers. As disadvantages the following may be mentioned:

1. It is complicated in wiring and depends upon the correct functioning of three relays, each having a set of contacts in series.

2. Will not operate on bus short circuits, and additional relays must be provided if such protection is desired.

3. The last line is non-automatic unless the locking relays are arranged for automatic reclosing after a definite time interval. The last line would then have instantaneous protection provided the relays were set above the full-load current of the line, but would be affected by through short circuits.

Split-Conductor Cable System

One company reports four installations of split-conductor cable as follows:

1. Four 350,000-cir. mil cables between generating and substation.

2. Two 350,000-cir. mil cables between substations.

3. Two 2/0 cables between generating station and customer's substation.

4. Two 250,000-cir. mil cables between substation and customer's substation.

On Installation No. 1 the feeders are tie lines connecting a generating station with an important substation, and a scheme which would disconnect a defective line at an earlier stage in the development of the fault and more quickly than is possible with over-current and uni-directional relays, was required in order to reduce as much as possible the disturbance to such an important part of the system. Split-conductor protection gave promise of better satisfying these conditions than any other scheme. The other installations are paired radial lines and were installed mainly to try out the scheme in other localities and under different conditions. Installations No. 3 and No. 4 supply customers who demand the least possible disturbance to their service.

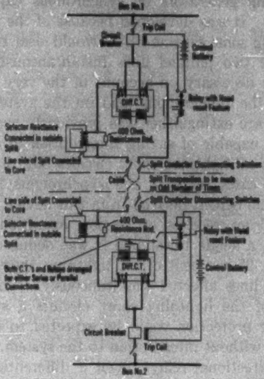
Bus No.1
Trip Coil
Circuit Breaker
Control Battery
Diff.C.T.
Relay with Hand reset Feature
Selector Reactance Connected in outside Split
400 Ohm. Resistance Rod.
Line side of Split Connected to Core
Split Conductor Disconnecting Switches
Cable
Split Transposition to be made an Odd Number of Times
Split Conductor Disconnecting Switches
Line side of Split Connected to Core
Selector Reactance Connected in outside Split
400 Ohm. Resistance Rod.
Relay with Hand reset Feature
Both C.T.'s and Relays arranged for either Series or Parallel Connections
Diff.C.T.
Control Battery
Circuit Breaker
Trip Coil
Bus No.2

FIG. 8—SCHEMATIC DIAGRAM OF SPLIT CONDUCTOR SCHEME

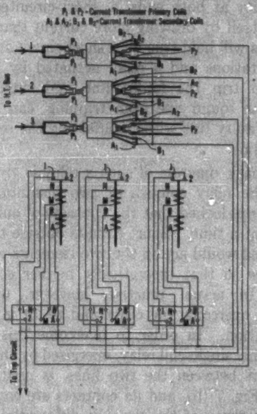
P1 & P2 - Current Transformer Primary Coils
A1 & A2; B1 & B2 - Current Transformer Secondary Coils
1
2
3
To H.T. Bus
P1
P2
A1
A2
B1
B2
To Trip Circuit

FIG. 9—TYPICAL WIRING DIAGRAM—SPLIT CONDUCTOR SCHEME

A schematic diagram of the installation is given in Fig. 8 and a typical wiring diagram in Fig. 9.

The differential current transformers are made up of two primary windings, differentially wound, and a single secondary winding divided into two sections, giving a ratio of 4 to 1 when in series and 8 to 1 when in parallel.

Single-pole, instantaneous, over-current relays of the two-coil type with hand-reset contacts are used.

The reactance coils are of the iron-core type with a 500-ohm resistance in parallel, and the value of the reactance depends upon the length and size of the cable. They are of about the same size and form as the current transformers.

The lines of installation No. 1 are all operated in parallel. The other installations are paired radial lines, the lines of each pair being operated in parallel.

The relays may be tested for current balance by inserting a low scale ammeter in series with the relay winding while the cable is heavily loaded. The oil circuit breaker may be tripped at any time by opening one of the split disconnecting switches. It has been found that a setting for 10 per cent unbalance works out satisfactorily.

The time that each of these installations have been in service is as follows:

Installation	No. 1	Feb. 20, 1918 to present date
"	No. 2	Sept. 29, 1917 " " "
"	No. 3	Jan. 6, 1918 " Aug. 21, 1920
"	No. 4	Sept. 29, 1917 " Dec. 28, 1918

All these split-conductor installations have proved satifactory but only installations No. 1 and No. 2 are now in service. Installation No. 3 was discontinued after a cable failure, as split-conductor cable could not be obtained in as short a time as was necessary which necessitated its replacement by standard cable. Installation No. 4 supplied service to a large customer who closed down his plant after completing war contracts.

As proof of the effectiveness of the split-conductor scheme of protection the following summary of operation was given.

Installation No. 1—There have been no incorrect operations. There have been six correct operations.

Installation No. 2—There have been two incorrect operations. In the first case a fault on a line between the generating station and another sub-station opened both lines at both ends. In the second case the oil circuit breaker on another line at the generating station failed and opened both split conductor lines at both ends. Of the four split conductor installations, this is the only one to have incorrect operation and its is believed that there is an unbalance somewhere in the connections which was not evident when checked by the usual methods and which caused the relays to operate under heavy surge conditions or on through short circuits. This is to be carefully checked, by actual test if necessary. There have been no cable failures and, therefore, no correct operations.

Installation No. 3—No faulty operations have taken place. There have been three correct operations, in each instance the faulty line being tripped out without opening any other lines.

Installation No. 4—No cable or apparatus failures or operations, either faulty or correct have occurred.

In every case of cable failure the line was cleared at such an early stage in the development of the fault that there was no perceptible voltage dip or other form of system disturbance.

Up to the present time no tests have been made to duplicate operating conditions and the operations which have occurred indicate neither the necessity of such tests nor the need of any change in the trial installations except as mentioned in the summary of operations of installation No. 2.

From the experience which this company has had with this scheme of protection it is considered superior to the over-current and uni-directional scheme in the following respects:

1. It does not require tapered time settings for selectivity and thus may have any number of substations in a loop or in tandem.
2. It does not require the calculation of short-circuit currents for relay settings.
3. The cable is disconnected at an early stage in the development of the fault, generally before the cable is badly damaged and with practically no dip in the voltage or shock to the system.
4. A breakdown in the primary winding of the differential current transformer or in the reactance coil causes the line to trip out, thus indicating an apparatus breakdown at the time of its occurrence.
5. The scheme is applicable to any number of lines and additional lines may be added without any change in the wiring or relay settings of the lines in service.

It is also considered to have the following disadvantages:

1. It is more expensive by about 20 per cent than standard cable with over-current and directional protection.
2. It requires special apparatus. The reactance coils, differential current transformers, double disconnecting switches and cable are special and are usually of slow delivery, which may cause considerable delay and inconvenience in case of breakdown, unless sufficient material is carried in stock to take care of any emergency.
3. It does not protect against bus short circuits, necessitating over-current relays if such protection is desired.

Pilot-Wire Scheme Using Differential Relays

One of the companies has tried a pilot-wire scheme on the balanced voltage principle, that is the e. m. fs. of the current transformers at each end of the pilot wire are opposed to each other. However, after a thorough test of this scheme, it has been superseded by another pilot-wire system which its originator has called a balanced differential system. This system makes use of a special differential relay having two coils with equal turns, and connected so that under normal operation the currents through these two coils are equal but in opposite directions. By reference to Fig. 10, it will be observed that the current from one of the current transformers divides into two equal parts, one part going through one coil of the relay, thence through the pilot wire to the other station, while the other half of the current flows through the relay and through a resistance which is adjusted to be equal to that of the pilot wire. It is easy to see that under normal conditions, no matter how heavy the current may be through the feeder, there will be no unbalanced current through the relay attempting to operate it. However when trouble occurs in the feeder, the current from the transformer at one end of the pilot wire will oppose the transformer at the other end, and, therefore, it will not divide evenly, relatively less current flowing through the pilot wire and more through the resistance so that the magnetic balance of the relay will be upset, causing it to operate.

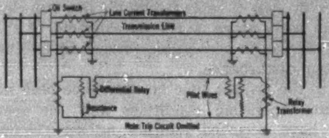

Fig. 10—Differential Relay Scheme—Two Pilot Wires

The system shown in Fig. 10 with two pilot wires will operate only when the cable fault involves current flowing to ground, but the system shown in Fig. 11, which requires three pilot wires, will operate no matter what may be the nature of the fault. It has been estimated that to protect a 5000-ft section of cable, the cost of the two-wire installation would be 90 per cent, and the cost of a three-wire installation 110 per cent of the cost of a standard installation of directional relays. For a 10,000-ft. length of cable, the cost would be respectively 135 per cent and 170 per cent of the cost of a directional relay installation.

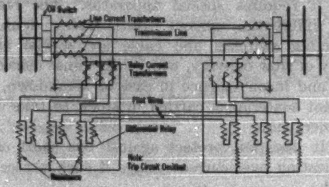

Fig. 11—Differential Relay Scheme—Three Pilot Wires

This company's network is quite extensive and it was feared that on many of their loops, where a number of substations are in series, the total time setting required on some of the over-current relays, in order that they might be properly selective, would be so high that the conventional over-current directional scheme would not be suitable. This pilot-wire scheme was therefore selected for use on certain sections to secure instantaneous operation and thereby reduce the time required on other relays. Furthermore, since most cable troubles start on a breakdown to ground, this scheme will, in the majority of cases, disconnect the faulty cable before the trouble has developed into a short circuit.

Since August 1918, the scheme using two pilot wires has been applied to 60 lines and the three-pilot-wire scheme to four lines. There have been 28 correct and 12 incorrect operations, the latter being due largely to the defective apparatus which was used on the first few installations. It is interesting to observe the causes of the false operations, which can be grouped as follows:

Defective apparatus and connections	6
Errors in making connections.......	4
Unbalance in the current circuit due to instrument installations.......	2
Total................	12

During the past two years there have been only two incorrect operations and it is reasonable to expect even less in the future.

The advantages of this scheme are:

1. Complete independence of relays on one line from all others.
2. Selective time settings are not required as the action is instantaneous.
3. High current settings are not required and short-circuit current calculations are unnecessary.
4. Special cable is not required as in the case of the split-conductor scheme.
5. The balancing operation is simple, requiring merely the adjustment of the series resistance.
6. Standard current transformers may be used and no high potential is induced in the line-current transformers.
7. The complexity of the network offers no difficulty in the application of the scheme except in the case of tapped lines.

The one disadvantage of this scheme lies in the cost of the pilot wire. For long transmission lines, induction type relays are preferable but for short lines or for a network this pilot-wire scheme has many advantages.

Differential Pilot Wire

One company reported that differential protection, using pilot wires, was originally tried out on several 110-kv. line sections but that it was abandoned because of very frequent interruptions which could not be satisfactorily explained.

On account of the high voltage of the system it was desirable to disconnect a faulty circuit instantaneously and this scheme was devised in the hope that it would meet the requirements. A schematic diagram of the installation is shown in Fig. 12. The longest section upon which it was installed was 51 miles and the shortest 13 miles. The neutral of the system was at first ungrounded, but was later grounded through a water resistance. One ground was located in the neutral of the step-up transformers and the other in the neutral of the step-down transformers at two places in the system.

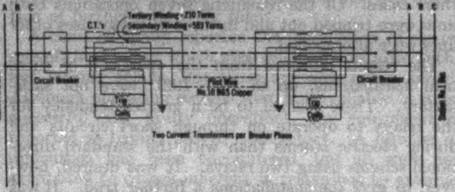
A
B
C
Tertiary Winding - 210 Turns
Secondary Winding - 583 Turns
C.T.'s
Circuit Breaker
Pilot Wire
No. 10 B&S Copper
Trip Coils
Two Current Transformers per Breaker Phase
Station No. 2 Bus
Station No. 1 Bus

Fig. 12—Schematic Diagram of Differential Pilot Wire Relay System

The special equipment required for the scheme consisted of bushing-type current transformers with secondary and tertiary windings. Ordinary alternating-current trip coils of rather high impedance were used as relays.

Referring to Fig. 12, the operation was as follows:

Under ordinary conditions of flow of power, the current flowing out of the circuit at the receiving end should be equal to that flowing into it at the transmitting end. Under these conditions, the voltage induced in the secondaries of the bushing type current transformers would be equal and opposite, and currents proportional to the line current would flow in the delta-connected tertiary windings, with no tendency to flow through the trip coils in parallel with them, since the resultant of the line currents would be zero. Thus, when any current flowed from the transmitting end without reaching the receiving end, as would be the result of a fault, the system would be unbalanced, and current would be forced through the trip coils to operate the circuit breakers.

The scheme was in service about two years. No adequate records of the various tests or operations are now available, but it was abandoned as unsatisfactory about 1913. The use of the ground for one conductor of the pilot-wire system may have been partly responsible for the defective operation of this scheme. This may apply, especially, on account of exposure to the power circuit which would normally indicate the desirability of proper relative transpositions in the pilot-wire circuit. It is also possible that an attempt was made to have the equipment too sensitive, and as inverse time over-current relays with mechanical trip were used on the same lines, it is probable that these operated simultaneously with the differential relays and thus destroyed selectivity.

This scheme is described chiefly as a matter of interest since it constitutes the only reported attempt to use such a scheme on a high-voltage overhead system.

III. Differential Power Schemes. The differential current schemes just described, though usually simple in equipment and installation are subject in some cases to disdavantage in that the line in trouble does not carry the greater current. Differential power protective schemes for parallel lines, however, are discriminating in their action in all cases and can be relied upon when the effectiveness of the simpler schemes may be doubtful.

A Modification of the Differential Power Scheme

One company reports the installation of the fundamental scheme described in the paper on Transmission Line Relay Protection in 1919, but the application has been modified by the introduction of auxiliary transformers across the secondaries of the current transformers. These are used first as balancing transformers, different ratios being provided so that differences in the main current transformer secondary currents may be compensated for; second, to permit grounding of the main current transformer secondaries without danger of interference with the operation of the relays; and third, under heavy short circuits the auxiliary transformers become saturated and limit the current flowing to the relays, thus preventing the tendency of the relays to "chatter".

In this installation elaborate arrangements have been made to substitute plain over-current for the differential power protection when operating changes require and provision has been made, by means of a differential direct-current relay and contactors arranged as a bridge, automatically to open the current transformer loop when only one line is in service, thus leaving plain directional protection on the line.

No operating results for this installation were supplied and it is described chiefly as an interesting modification of a well-known scheme.

Differential Duo-Directional Relay Schemes

Several companies reported installations of differential duo-directional relays. A simplified diagram of this scheme is shown in Fig. 13. No special equipment is required, standard over-current and directional relays, with double-throw contacts on the directional element, being used. The principle of operation of the scheme is the same as that described in the paper on Transmission Line Relay Protection in 1919.

It may also be well to point out that if protection against balanced or bus faults is desired, over-current relays may be inserted in each current transformer secondary circuit to take care of such requirements.

Outside of the usual phasing tests as made in the standard uni-directional relay installation, there are no special precautions necessary except to make a check for zero current by inserting a low-reading ammeter in series with the relay current coil while the lines are heavily loaded.

One company reported two trial installations of these relays which were installed because of a desire to find a balanced scheme, applicable to two lines which would not require tapered settings for selectivity and would not be affected by through short circuits.

Installation No. 1 has been in service since April 1919. Up to June 1921, there were twenty-five operations, two of which were correct and twenty-three faulty.

Of the two correct operations, one occurred during a sleet storm, one line being out of service. The other opened at both ends and two phases were found to be faulty. No other lines came out, and although classed as a correct operation it is not a fair trial of the scheme as applied to paired line protection. The other correct operation occurred during an electrical storm.

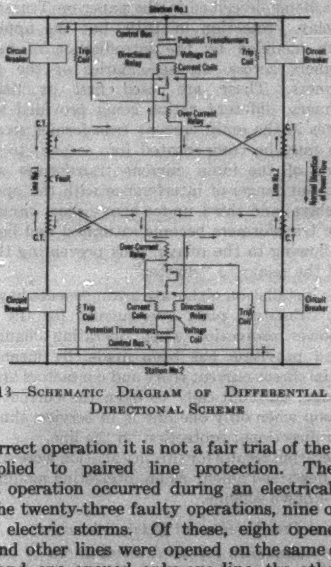

FIG. 13—SCHEMATIC DIAGRAM OF DIFFERENTIAL DUO-DIRECTIONAL SCHEME

Of the twenty-three faulty operations, nine occurred during electric storms. Of these, eight opened both lines and other lines were opened on the same disturbance, and one opened only one line, the other being out of service at the time, but other lines on the system were opened. Of the remaining fourteen operations, there were three cases where both lines were opened but no others, and eleven cases where both lines were opened with others.

Installation No. 2 was put into service in July 1919 and up to July 1921 there were twelve operations, three being correct and nine faulty.

In one of the three correct operations one of the paired lines was out of service at the time so the operation was similar to that of installation No. 1. In another operation faults occurred on both lines and both were cleared. The third operation was the only case of a fault occurring on one line of the pair, in which the faulty line was cleared and the healthy line remained in service.

Of the nine faulty operations, two occurred during electric storms. No cause was found but both lines were opened and other lines were opened in one of these cases. Of the remaining seven operations both lines were tripped out and in three of these cases other lines were also opened.

The results obtained from the operation of these trial installations, up to June 1921, were not satisfactory. There seemed to be a greater tendency for the relays to operate on through short circuits and during electric storms than with the standard directional scheme using two relays. It was desired, however, to give the installations a further trial. It was thought that the wattmeter element to which the double contacts are attached, having less than one-sixteenth inch movement from one contact position to the other, upon clearing the faulty line rebounds from one contact to the other and thus trips out the healthy line. It was, therefore, decided to install locking relays which would make inoperative, for a definite time, the oil circuit breaker trip on one line when the relays are actuated to trip the other line of the pair. In this way it was hoped to overcome the difficulty.

These locking relays were put in service on installation No. 1 in June 1921, and up to March 1922 there were nine operations, six of which were satisfactory and three faulty. Of the six correct operations two occurred during storms and four were due to flashovers. Of the three faulty operations, one occurred during an electrical storm, with one line of the pair out of service, a fault on another line caused the remaining line of the pair to trip out. In another case both lines tripped out when one line was tried out after a correct operation which was due to operating conditions and not the fault of the relay. In the third case an end fault on one line tripped both lines out. The relays have been reset for this end fault condition.

On installation No. 2 the locking relays were put into service in July 1921 and to March 1922 there has been one operation. This occurred during an electric storm and was satisfactory.

From these last operating results it would seem that the locking relays have, to a large extent, overcome the difficulties originally experienced. It is intended, therefore, to retain both installations and give them further trial.

Except in the matter of lessened panel space and the slightly smaller investment required for the duo-directional equipment over the double unidirectional equipment, this company considers that the trial installations have shown no advantage.

Another company reports the installation of nine groups of these duo-directional relays. Locking relays are not used on any of these installations and the operating records show that over a period of fifteen months after they were put into service, the operation was correct in about 70 per cent of the cases of trouble. These results were not considered entirely satisfactory but the installations are to be retained with the intention of further improving them.

A third company reported the installation of eleven sets of these relays which were originally installed without locking relays, but these are now being added. Although operating records were not available to show successful and faulty operations, the equipment is reported as having proved satisfactory. A number of difficulties has been encountered but all were not attributed to causes inherent in relays but to external faults such as defects in wiring and burnouts.

A fourth company reports the use of two groups of these relays but no definite operating records were given so that it was not possible to determine whether the installation was satisfactory.

The fifth reported that four groups of these relays were in use but the operating results as given were not sufficiently definite to determine what success had been obtained.

DIFFERENTIAL POWER SCHEME USING BUS SECTION CIRCUIT BREAKER

One power company reports the use of a bus-section circuit breaker tripped by over-current relays to provide protection in case of a bus or other balanced fault. An auxiliary switch then serves to inject additional time when this section circuit breaker opens, practically resulting in time over-current and directional protection until the circuits are again paralleled by the section circuit breaker.

Except in the case of balanced faults the conventional differential power scheme is used and the method of sectionalizing the bus has the advantage of maintaining service over one line and on approximately one-half the feeders in the station in case of bus failure.

IV. Ground Relay Schemes. When a system neutral is grounded through a comparatively high resistance the usual over-current relay set for short-circuit protection may not be able to operate in case of ground faults. It appears to be accepted practise in such instances to connect a "residual" relay in the neutral lead of the current transformer secondaries. This relay will be energized only in case of a ground on the system and accordingly may be set for a very much lower value than the "phase" relays. These residual relays may be given time and current grading in the same manner as the phase relays. The general practise is to use phase relays in each of the three phases and the residual relay in the neutral. This is recommended on account of the fact that the third phase relay provides added insurance of protection in case of either phase short circuits or faults to ground.

Pilot Wire Protection against Grounds

On a 23,000-volt cable system looping frequently through substations and further interconnected into a network so extensive and complicated as to involve rather high and difficult settings, the pilot wire protective scheme shown in Fig. 14 has been installed in five of the shorter sections with a sixth now being added.

From the diagram it will be noted that the protective equipment is connected to the neutral circuit of the main current transformers and that practically no current will flow in any of the tertiary circuits under normal conditions or under abnormal conditions not involving a ground. This insures against any possibility of operation for overloads or for any faults which do not go to ground. This characteristic may be considered a disadvantage by some engineers but the operating company in this case feels that the proportion of faults which do not either start with, or become, grounds is sufficiently small to justify the reduction in equipment secured and the additional safeguard against operation on through faults.

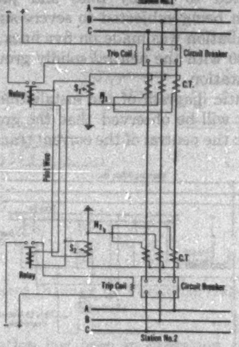

FIG. 14—DIAGRAM SHOWING SCHEME OF PILOT WIRE PROTECTION AGAINST GROUNDS

If a ground is assumed as occurring on some more remote section, equal currents will flow in the neutral circuits N_1 and N_2; secondary current transformers S_1 and S_2 connected in these circuits (principally to permit grounding of the main current transformer secondaries for safety reasons) will then cause a current to circulate through pilot wires A and B. No current flows through the relays, however, due to the use of the third pilot wire R which permits connecting this relay circuit to equal potential points regardless of the drop in the other two pilot conductors. If, on the other hand, the ground should occur on the section under consideration there will again be currents in the neutral but in this case they will be unequal or opposed and accordingly a current approximately proportional to the fault current will flow through the relays and pilot conductor *R*. This will cause relays to operate and the circuit to be isolated.

These five sections have been in service from one to two years. During this time none of these cables have failed. Therefore positive data on the operation of this equipment are lacking. A number of artificial faults have been applied, and the relays operated correctly in every case.

The advantages of this scheme have been given above. Granting that protection against grounds is all that is required the only practical disadvantage consists in the additional cost of the third pilot wire.

Selective Ground Relay Scheme

One company reported the trial installation of a selective ground relay scheme which was adopted with the expectation that faults of slow development would be cleared at an earlier stage than is possible with phase relays, thus preventing the trouble from being communicated to nearby lines and preventing the system from being subjected to severe shock.

The installation was made on five lines and the voltage is 26,400 with the neutral solidly grounded, at the generating station.

A schematic diagram of the installation is shown in Fig. 15. It will be observed that the ground relay is connected in the neutral of the current transformer bank and that where over-current relays are used their contacts are paralleled with those of the ground relays. When the over-current directional combination is used the ground relay contacts are arranged to short circuit the over-current element, thus leaving the wattmeter element to discriminate as to direction of power flow. No special equipment is necessary except that the directional relays are equipped with an extra terminal which taps the trip circuit between the contacts on the two elements.

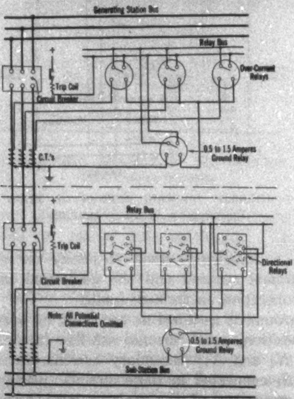
Generating Station Bus
Relay Bus
Trip Coil
Circuit Breaker
Over-Current Relays
0.5 to 1.5 Amperes Ground Relay
C.T.'s
Relay Bus
Trip Coil
Circuit Breaker
Directional Relays
Note: All Potential Connections Omitted
0.5 to 1.5 Amperes Ground Relay
Sub-Station Bus

FIG. 15—DIAGRAM OF SELECTIVE GROUND RELAY SCHEME

The ground relays are induction type over-current, having gears interposed between the disk-shaft and the contacts. They have a minimum operating current range of from 0.5 to 2.5 amperes and the energy consumed is low, being in the neighborhood of 2 to 3 volt-amperes. The current transformers are of the standard through or bushing type.

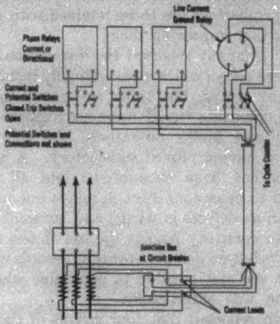
Low Current Ground Relay
Phase Relays Current or Directional
Current and Potential Switches Closed Trip Switches Open
Potential Switches and Connections not shown
To Cycle Counter
Junction Box at Circuit Breaker
Current Leads

FIG. 16—METHOD OF TESTING GROUND RELAYS WHEN USED WITH BUSHING-TYPE CURRENT TRANSFORMERS

The relays are set by applying test current to the secondary terminals of one of the current transformers, with the three phase relays and the ground relays in circuit, as shown in Fig. 16. The secondary test current is determined by dividing the primary ground current by the turn ratio of the current transformers. By this method of testing, the exciting current of the current transformers and the shunting effect of the circuit formed by the two current transformers and phase relays on the other two phases are taken into consideration. With bushing-type current transformers these factors greatly modify the setting unless allowance is made by calculation or by the test method.

These installations have been in service from December 28, 1920 to the present time. Prior to January 1921 there were two correct operations both of which indicate that the ground relays operated at an early stage in the development of the fault.

Since January 1921, a 150-ohm ground resistance has been installed limiting the ground current to 100 amperes. The following summary of operations show the results which have been obtained: Up to March 1922, there were seventeen operations, four of which were faulty and thirteen correct. In the case of the faulty operations, two lines, not on the same pole line, operated upon a fault or flashover on one of these lines.

No lines were found to be bad. In July 1921, the settings were changed on these relays, and since then no faulty operations have occurred. Of the thirteen correct operations, in six cases one line only came out with no lines bad, but the dip in voltage gave evidence of a flashover. In seven cases, two lines on the same pole line opened, two cases a fault occurred on one line and one case a fault occurred on both lines, while in the other four cases no lines were found to be faulty, but a flashover was evidenced by the dip in voltage. These are counted as satisfactory operations, inasmuch as the lines are in a section frequented by strong winds. The lines are all closely spaced on the crossarms and experience has shown that in a large percentage of cases a flashover on one line carried over to the other lines.

The above summary does not include operation during electric storms. There have been three or four heavy storms in which the load dispatchers were not able to make any record of the operations.

The reporting company has since equipped another 26,400-volt system, having a 150-ohm neutral resistance with selective ground relays operating on bushing type current transformers. This system consists of four lines with widely spaced conductors arranged in a loop. No operating data for this installation are available.

Another company reports the installation of a residual relay, of the type described in the foregoing, in the neutral lead of the current transformer secondaries on a differential power scheme. These installations are at the receiving end of three sections of 110-kv. double-circuit lines in tandem. The function is exactly the same as that of the residual relay at the receiving end of the foregoing scheme. These installations have only recently gone into service and therefore no operating records are available.

Selective Differential Ground Relay Scheme

One of the companies is making use of the conventional differential power scheme, using directional relays on its high-voltage system, consisting of two parallel lines with a number of substations, sectionalizing them at various points. But in addition to the differential relays for protection against short circuits the company makes use of induction-type differential relays connected in the neutral connection of the current transformers so as to disconnect a grounded transmission line. This is necessary because the high-tension neutral is grounded through a comparatively high resistance. This system has not yet gone into operation, but service tests are now being conducted, and will be reported some time in the near future.

Potential Ground Relay System

Another company reports a ground relay system which was devised to protect underground three-conductor lead cables from excessive potential strains upon the conductor insulation of the other phases when a ground develops on one phase. The cables are operated at 15,000 volts and each line is isolated from other parts of the system. Since the system is ungrounded practically no ground current flows when a ground occurs but the potential between the other conductors and sheath is raised from star to line voltage.

A schematic diagram of the installation is shown in Fig. 17. No special equipment is used, all apparatus being standard. The relay is of the over-current induction type and has a minimum operating current range of 0.5 to 1.5 amperes.

Referring to Fig. 17, when a ground occurs on *A*, for example, the potential transformer on that phase becomes short circuited, since the primary side of the potential transformers are connected in star and the neutral grounded. This in turn causes a current of low value to circulate through the potential transformer secondaries which are connected in delta through the over-current relay. Thus the relay will operate for a ground on any phase and clear the defective line.

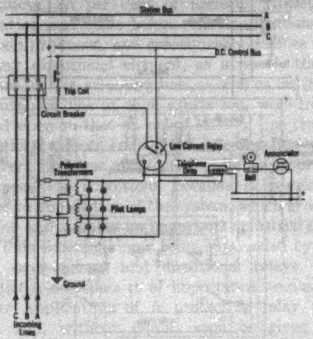

FIG. 17—SCHEMATIC DIAGRAM OF POTENTIAL GROUND RELAY SYSTEM

This installation has been in operation since 1917, though no operating data are given for the period prior to 1919. During 1919 and 1920 there were 18 cases of correct operation and 2 cases of incorrect operation.

While the operation of the scheme has proved satisfactory it has been abandoned in favor of a scheme which will discriminate between lines and thus permit paralleling.

The installation has a threefold advantage in that it is simple in detail, is very quick to remove the trouble and functions without requiring any appreciable current to be flowing in the fault.

Its one great disadvantage is that, in case of a ground all the apparatus which it protects is disconnected. It, therefore, prevents the paralleling of feeders, as in an interconnected network or on parallel feeders all lines are likely to be opened on account of static unbalance.

GROUND SELECTOR RELAY SCHEME[3]

In order to overcome troubles due to grounds on a 12,000-volt ungrounded distribution system, one company reports the installation of a ground selector-scheme. The distribution system in question consists of approximately 80 miles of underground and the same amount of overhead distribution all fed from the same bus bar. Because of the extent of the system, grounds were quite frequent and cross short circuits sometimes developed before the ground could be located and cleared. This usually meant an interruption to a more or less extensive portion of the system. Some means of detecting and clearing the ground immediately upon its development was, therefore, very desirable and since the system was delta-connected this meant either the installation of grounding transformers or the development of some means of accomplishing the same results. After a thorough study of the situation it was decided to adopt the ground selector scheme shown in Fig. 18.

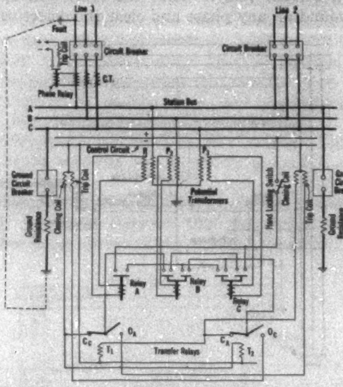

FIG. 18—SCHEMATIC DIAGRAM OF GROUND SELECTOR RELAY SYSTEM

The principle of this ground selector is that any ground occurring on the system will immediately be developed into a short circuit by automatically grounding another phase at the base station and artificially completing a short circuit path. Short circuit current will then flow out into the fault, operating the phase relays and clearing the defective feeder in the same manner as if it was short-circuited. The artificial ground is made at the base station bus through an oil circuit breaker which is automatically opened as soon as the defective feeder is cleared, thus restoring the system to the normal condition. The circuit breaker is connected to ground through a very low resistance water rheostat which does not appreciably affect the magnitude of the fault current under the most limited current conditions, but has the advantage of sustaining the bus bar voltage in case of grounds near the base station, thus helping to keep the synchronous load in step.

Referring to Fig. 18, the essential features of the scheme are as follows:

The primaries of the three potential transformers are connected in star and the neutral point grounded. The secondaries of these transformers are each connected to an over-voltage relay, the action of any two of which will close the proper ground circuit breaker. So-called transfer relays are provided to insure the automatic opening of the circuit breaker as soon as the grounded feeder has been cleared.

Normally the three phases of the system will be balanced to ground, the potential on the transformers being the same and equal to 58 per cent of the voltage between phases. A ground on one phase will tend to lower the voltage on the corresponding transformer and the voltage on the other two phases will tend to rise to line voltage of 1.73 per cent of the normal voltage to ground. The over-voltage on the two sound phases operates the corresponding over-voltage relays and closes the ground circuit breaker.

As a specific example, assume a ground on Phase *A* of Line 1. This results in a high voltage on phases *B* and *C*, operating their corresponding relays and closing the ground circuit breaker on phase *C*. There is then a complete short circuit between phases *A* and *C* and the phase relays clear the faulty line. This leaves the grounding circuit breaker closed, resulting in a ground on phase *C*, and except for the transfer relay the other ground circuit breaker would close, due to the high voltage on phases *A* and *B*, and cause a bus short circuit. The transfer relay, however, locks the closing circuit of the second ground circuit breaker immediately upon the closing of the first one and at the same time prepares for the tripping of the one which has been closed. When the ground circuit breaker on phase *C* closes it energizes the coil of the transfer relay *T*-2, throwing the lever over into the other contact position. In this position of the lever, high voltage on phases *A* and *B* will trip the ground circuit breaker on phase *C* and reestablish normal conditions instead of wrongly closing phase *A* to ground through the other circuit breaker. In a like manner a defective feeder which may become grounded on phase *B* or *C*, will be cleared and normal conditions reestablished.

Other features which are not shown in the diagram but which are added to make the device practical are as follows:

A differential potential relay, responding only to unbalanced potential to ground, to prevent the over-voltage relays from operating on balanced over-voltage.

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3. "Relay Protective Features of The Toronto Power Company's Transmission and Distribution System" by P. Ackerman. The Engineering Institute of Canada. April 1921.

Such action would not, in itself, be harmful, since the transfer relays would prevent the closing of the ground circuit breakers, but it would necessitate resetting the device, as the transfer relays are not automatically reset. It has been found advantageous to limit the device to one operation since automatic resetting might cause trouble if a ground should develop into a short circuit and clear the feeder before the ground circuit breaker is completely closed. The transfer relays are, therefore, arranged for hand resetting.

The ground circuit breakers are equipped with over-current relays set high enough to permit the feeder phase relays to operate before the ground circuit breaker opens. They are also provided with complete electric control which permits the operator to operate them manually if occasion arises. In addition, a hand locking switch is provided so that the automatic features can be removed without interfering with the hand control of the grounding circuit breaker.

This ground selector scheme was put into service in 1918 and its operation has been very satisfactory. During a period covering something over two years, operating records show that it effectively cleared a total of 86 grounds. Of these 86 cases of trouble, 40 were classed as permanent and were due to such causes as cable troubles, bad insulators, bad current transformers, operators' mistakes and testing faulty feeders. The remaining 46 were classed as transient troubles and were due to lightning and unknown causes probably customers' grounds or outside interference.

During this same period there were 41 momentary, self-clearing grounds, due to unknown causes, starting the ground selector but clearing before the ground circuit breaker closed.

The advantage of this ground selector scheme seems to be in the cost as compared to other schemes. The two alternative schemes for accomplishing the same result are as follows:

1. The installation of low reactance grounding transformers of large capacity so that sufficient current to operate the phase relays would be obtained, even on very remote grounds.
2. The installation of smaller capacity grounding transformers of higher reactance and the addition of special ground relays of low setting, which would take care of limited ground current.

The first was undesirable, in the case of the reporting company, on account of the inherent high cost of the high-capacity transformers and the second was equally undesirable because of the expensive relay and current transformer equipment required. Additional current transformers would have been necessary because all those available were fully loaded and the addition of new ones would have introduced complications on account of space limitations. The idea of grounding transformers was, therefore, abandoned in favor of the ground selector scheme.

The chief disadvantage is the loss of the advantage of a permanently grounded system. There is also the possible disadvantage of having no ground protection in case a ground should occur before the device is reset after an operation.

V. The Under-Voltage and Over-Current Combination. When a short circuit occurs on any part of a system the potential will be a minimum at the point of fault, increasing as the source is approached. This, therefore, provides another means of discrimination, which, in combination with over-current devices, may, under favorable circumstances such as long overhead lines, greatly increase the certainty of selectivity.

In the report of the Protective Devices Committee, submitted June 24, 1919, entitled "Transmission Line Relay Protection," there was described a method of automatically sectionalizing transmission lines, which made use of under-voltage and over-current relays. One of the companies installed this system about twelve years ago, and it has been estimated that the operation of the system, as far as the relays are concerned, has been about 85 per cent of perfect. However, this installation was made before reliable directional relays had been produced, and consequently, it does not contain any directional element, as a result, the circuit breakers on the incoming line, as well as on the defective outgoing line at each substation, were frequently tripped open so that on many cases of line trouble the substations at both ends of the defective line were lost. However, this was considered quite an improvement over previous conditions because it restricted the trouble to one section of the system, which is an important one and supplies an important industrial community. This scheme is now being superseded by conventional over-current and directional relays, but the Committee considers it of importance because it is a pioneer application of a protective relay principle which will, without doubt, soon be given another trial using more highly developed apparatus of greater refinement.

The Calculation of Short-Circuit Currents

A fault on a system produces an abnormal condition, which has no relation to normal loads and overloads, and in order to obtain selective action from over-current and directional relays, it is necessary to set them for the currents flowing under this condition. Feeder over loads can be taken care of by attention on the part of the operators.

This necessitates the calculation of short-circuit current values as a basis for relay settings. These calculations have been covered by numerous writers, so that this article will only give a description of a generally used method with references for those who desire further to investigate the subject.

Practically all short-circuit current calculations are made with reactance alone, resistance and capacity being neglected. In general, neglecting resistance and capacity does not produce an appreciable error except in certain types of systems. This reduces the calculations to an application of Ohm's and Kirchoff's laws, using reactance in place of resistance. One method is to express the reactance of all generators, transformers, lines and other apparatus in ohms from one phase to neutral, and by adding up the reactance from the point of short circuit, to and including the generators, and dividing the sum into the voltage to neutral, the instantaneous value of the short-circuit current is found. This is the principle of the usual methods of calculations, but in systems having two or more different voltages it is necessary to express all the reactances in terms of one voltage and as the reactance of most apparatus is expressed in terms of percentage which is independent of voltage, and as line reactance in ohms can be easily converted into a percentage basis, the percentage method is generally preferred.

This method is described in an article by H. R. Wilson on page 475 of the *G. E. Review* for June 1916, in an article by W. W. Lewis, page 140, *G. E. Review* of February 1919, and in the article on "Rating and Selection of Oil Circuit Breakers" by Messrs. Hewlett, Mahoney and Burnham on page 123, TRANSACTIONS of A. I. E. E. 1918.

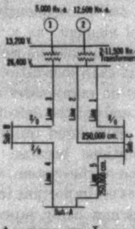

FIG. 19—LAYOUT ASSUMED TO ILLUSTRATE CALCULATION OF SHORT-CIRCUIT CURRENT

A brief description of this method is as follows:

All reactance of generators, lines, transformers, reactance coils and other apparatus is expressed as per cent reactance at a common kv-a. base, arbitrarily selected. The various reactances are converted up or down as the case may be, to this base. The combined reactance from the generator neutrals to the point of short circuit is determined and it is assumed that the entire voltage of the generators is used between these two points. Then

1. Instantaneous kv-a.

$$= \frac{\text{kv-a. base}}{\text{reactance to point of fault}}$$

Example. With the layout given in Fig. 19 the calculations are as follows:

Line (1)—35,300 ft.
Spacing $24 \times 24 \times 34$ $S = 27$ in.
Reactance per 1000 ft. = 0.1191 ohms
Total ohms reactance = 4.2
Per cent reactance on 10,000 kv-a. base = 6.0

In the same manner:

	Length	Spacing inches	Ohms reactance	Per cent reactance on 10,000 kv-a. base
Line (2)...	34,000 ft.	24 × 40 × 64	4.12	5.9
(3)...	56,000 ft.	24 × 24 × 34	6.70	9.6
(4)...	19,900 ft.	24 × 24 × 34	2.37	3.4
(5)...	33,400 ft.	24 × 40 × 64	4.04	5.8

REACTANCE OF APPARATUS

Apparatus	Kv-a. rating	Per cent Reactance	Per cent reactance on 10,000 kv-a. base
Generator No. 1......	5000	5	10.0
" " 2......	12500	12	9.6
Transformer " 1......	11500	5.75	5.0
" " 2......	11500	5.75	5.0

2. Reactance of the two generators in parallel
$= 1/10 + 1/9.6 = 1/X \qquad X = 4.9$ per cent
3. Reactance of the two transformers
$1/5 + 1/5 = 1/X \qquad X = 2.5$ per cent
4. Reactance of Lines 1 and 2 in parallel
$1/6 + 1/5.9 = 1/X \qquad X = 2.98$ per cent
5. Reactance of Line 3 + Line 4
$9.6 + 3.4 = 13.0$ per cent
6. Reactance of (4) + Line 5
$2.98 + 5.8 = 8.78$ per cent
7. Reactance of (5) in parallel with (6)
$$\frac{1}{13.0} + \frac{1}{8.78} = 1/X \qquad X = 5.3 \text{ per cent}$$
8. Reactance from Generators to Bus A
$(2) + (3) + (7) = 4.9 + 2.5 + 5.3 = 12.7$ per cent
9. Instantaneous Short-circuit kv-a.
$$\text{From (1)} = \frac{10000 \times 100}{12.7} = 78800$$

The instantaneous value decreases to the sustained short circuit value at a rate depending on the amount of reactance, generator characteristics, power factor of load on the generator at the time of the fault and other factors. Curves plotted from oscillograms taken on standard generators showing the current decrease for different values of reactance, are given in the paper by Messrs. Hewlett, Mahoney and Burnham, "Rating and Selection of Oil Circuit Breakers," on page 122 of the 1918 TRANSACTIONS of the A. I. E. E.

If the short circuit value given above is to be used with a relay, intended to operate under these conditions in 1.2 seconds, the usual method is to set the relay for the current value at the end of the interval. To use the decrement curves, it is necessary to use the reactance of the point of short circuit based on the total generating capacity. Converting the instantaneous short circuit kv-a. (9) to a per cent reactance based on the total generating capacity of the system.

Per cent reactance at 17500 kv-a.

$$= \frac{17500}{78800} \times 100 = 22.2 \text{ per cent.}$$

Referring to the decrement curves for 22.2 per cent reactance and 1.2 seconds the number of times full load current is found to be 2.52. Therefore, short circuit current at 1.2 seconds

$$= \frac{2.52 \times \text{gen. kv-a.} \times 1000}{1.73 \times \text{line voltage}}$$

$$= \frac{2.25 \times 17{,}500 \times 1000}{1.73 \times 26{,}400} = 964 \text{ amperes}$$

When the system has lines other than in parallel-tandem arrangement or is fed by more than one generating station, the solution becomes more difficult and if the network is complicated, the process becomes too tedious to be practical. Simple network solutions are given in the two references above and methods of solving networks are described in articles by R. D. Evans and Charles Fortescue on pages 345 and 350 respectively in the *Electric Journal* of August 1919.

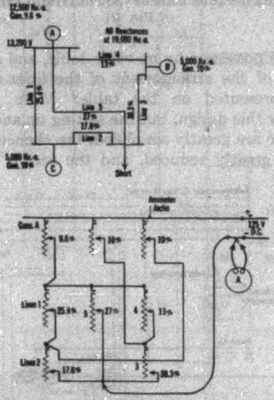

FIG. 20—TYPICAL LAYOUT AND SET-UP FOR CALCULATING TABLE

Calculating Table. The difficulty in the complete mathematical method lies in determining the system reactance to the point of short circuit, and the distribution of current among the many lines and generators. The calculating table covers this step in the process.

The table consists of a number of adjustable rheostats that are given an arbitrary rating. The original table and many built since, have the rheostats rated at 125 volts and a normal current of 0.2 ampere. The rheostats are calibrated and marked with some form of scale so that with 125 volts applied across the resistance the 0.2 ampere point is 100 per cent reactance, the 0.4 ampere point 50 per cent, etc., resistances of the value of 500 to 1200 ohms being used giving a reactance range from 0 to 80 per cent and 0 to 180 per cent approximately. Leads enable the resistances to be interconnected as the generators and various elements of a system. One end of the generator rheostat is connected to one side of the 125 volt source and the point of short circuit is connected to the other side. An ammeter jack in each rheostat circuit allows the current to be read with an ammeter.

The set-up of a more complicated problem is given in Fig. 20.

The ammeter inserted in the negative lead reads 1.7 amperes and, since 0.2 amperes is equal to 100 per cent reactance on the table basis, 1.7/2 = 8.5 times the table base in kv-a. The readings for all elements are as follows:

		Generators			Lines				
	Total	A	B	C	1	2	3	4	5
Actual readings.	1.7	0.56	0.46	0.694	0.068	0.76	0.396	0.058	0.532
No. of times normal.........	8.5	2.8	2.3	3.47	0.34	3.8	1.98	0.29	2.66

It is interesting to note that the flow over line 4, is from *B* towards *A*. This is directly indicated by the ammeter in the table set-up.

Instantaneous kv-a. = 8.5 × 10,000 = 85,000
Instantaneous amperes at 13,200 volts = 3720
Generating capacity = 22,500
Per cent reactance on generating capacity base

$$= \frac{22{,}500}{85000} \times 100 = 26.5 \text{ per cent.}$$

The distribution of the current in any part of the network may be determined as follows:

Current over line 2

$$= 3720 \times 3.8/8.5 = 1660 \text{ amperes}$$

The remaining part of the calculations and the use of the decrement curves are exactly the same as in the mathematical solution.

The original calculating table was described in the *G. E. review* page 901—August 1916. Other tables have been described in the *G. E. Review* of February 1919, page 140—August 1920, page 669 and *Electric Journal* August 1919, page 345. The first tables were actually in the form of tables, the later ones are in the form of a panel or cabinet.

In the latest boards, the plugging is done with telephone jacks and cord circuits, which makes a somewhat more compact arrangement and the leads of each rheostat are looped through telephone keys within reach of the operator so that the current in any part of the table may be read by the pressing of a key, without "plugging" an ammeter jack in circuit, as was necessary in the first designs.

One of the latest tables built is shown in Figs. 21 and 22.

This table was built by the testing department of the Commonwealth Edison Company, and consists of an oak cabinet, in the lower portion of which are mounted 60 adjustable rheostats, five on each of twelve panels; 60 pairs of telephone switchboard cords, connected through switch keys to the rheostats; a flush type ammeter and voltmeter; a reversing switch and shunt selector switch for the ammeter and the main switch for the table. On the upper panel are 30 horizontal rows of jacks, each row forming a bus, but except for the lower two rows not permanently connected to the lower part of the table. The first and second rows are the positive and negative buses of the table and are connected to terminal blocks at each end and to the voltmeter and the main switch.

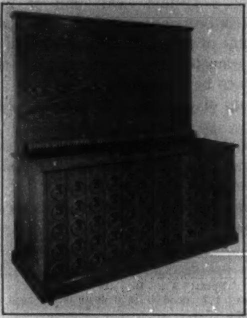

FIG. 21—VIEW OF A LATE DESIGN OF CALCULATING TABLE

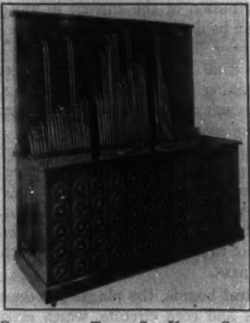

FIG. 22—CALCULATING TABLE SET UP FOR SYSTEM SHOWN IN FIG. 25

The rheostats each consist of four enameled resistance units, two of 500 ohms each with 100-ohm taps, and two of 50 ohms each with 10-ohm taps. Each rheostat is therefore adjustable from 0 to 1100 ohms in steps of 10 ohms. The mounting of the resistance units is shown in Fig. 23.

The switch keys in the circuit of each pair of cords and rheostat furnish means for readily connecting these circuits to the ammeter bus. A wiring diagram is shown in Fig. 24. Only one circuit is shown in this diagram, as all the others are similar.

The arrangement of horizontal busses on the upper panel makes unnecessary any crossing of cords. This is a feature possessed by no other table, and is possible regardless of the arrangement of the lines or station busses represented on the table. More jacks are required by this design, but the setting up and working of the table are greatly simplified, the chances of making errors greatly reduced, and the set-up is always readily traced or checked. Fig. 22 shows the table set up to represent the network in Fig. 25.

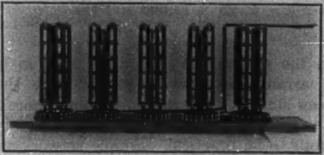

FIG. 23—RESISTANCE UNIT OF CALCULATING TABLE SHOWN IN FIG. 21

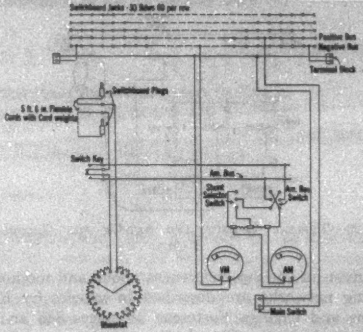

FIG. 24—DIAGRAM OF CONNECTIONS—CALCULATING TABLE

Since the photographs were taken, there have been added card holders in each row of jacks, mounted in the two vertical blank spaces on the upper panel, in which slips may be inserted, giving the names of the station or substation for the set-up; also brass dial plates for each rheostat, giving the number of the rheostat and the number of each step.

A few companies have made tables with fixed resistances, each resistance representing a specific line, generator, etc. in the system. Where the elements in a system are not numerous and in cases where changes are not frequent, this cuts down the cost of the table considerably. In one form of a calculating "board" using fixed resistances, the resistance to the point of short circuit is measured by a self-contained Wheatstone bridge. The current distribution may be calculated by obtaining the potential drops at the various points in the network.

The tables and boards have been found valuable for calculating short-circuit currents for the selection of oil circuit breakers as the method of calculation is the same as described here. The table also forms an easy way to determine the size of reactance coils necessary in designing station bus layouts, as the resistances representing the reactance coils can be varied until the short-circuit value is reduced to the amount that the oil circuit breakers can safely interrupt. Various schemes can be quickly set up and the relative effectiveness of the reactors determined.

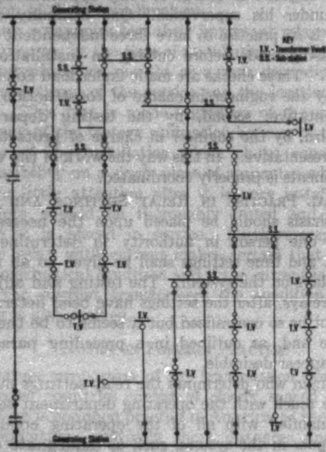

FIG. 25—DIAGRAM OF SYSTEM SET-UP ON TABLE IN FIG. 22

Inasmuch as the use of the table necessitates neglecting either the resistance or reactance of the various system elements, voltage measurements are not accurate in general.

The error in neglecting the resistance depends on the type of system. Where there are numerous reactance coils or transformers between the generators and the various substation busses, the error is not appreciable. In the article by H. R. Wilson on page 478 of the *G. E. Review* for June 1916, previously referred to as open wire system with 13,200-volt and 2300-volt generators, 88,000 volt lines and step-up and step-down transformers, the error between the resistance—reactance calculations and the reactance calculations, is 2 per cent. In a system where there are no transformers or reactance coils this error becomes greater. The magnitude of this error will depend on the system and a study of this condition for a system consisting of cables or for a system without reactance coils or transformers, should be made to see if the table may be used with a fair degree of accuracy. For a complicated network, however, the table is practically the only solution, but it is well to determine approximately the amount of the error.

The error between the mathematical solution (neglecting resistance) and the similar table solution varies with the number of elements in the set-up and the values of reactance used to set the rheostats. Where the reactance values were such that the rheostats were set well up on the scale, and when there were a number of elements in the set-up, the table figures have checked the mathematical calculations to 1 per cent or less. If possible the table kv-a. base should be changed to obtain reactance figures that will bring the rheostat pointers well up on the scale, values of 50 per cent or more being preferable to 5 to 20 per cent.

In regard to errors it should be remembered that the table figures do not need to be of a high degree of accuracy, as there is considerable error in the reactance values, especially the open wire figures, and the variations in operating conditions are generally so great that the errors in the table and those due to neglecting resistances, are not appreciable.

In obtaining reactance values on generators from the manufacturers, it is important that the reactance obtained be the transient or inherent value and that it be applicable to the decrement curves. It is quite common to furnish the synchronous or sustained value of reactance unless otherwise specified.

A close study of operating conditions is required to determine the generating capacity to be used in the calculations, as there is generally a variation of capacity during each 24 hours, during the week and during the year.

In addition to taking into consideration the variation of capacity in stations, it is also necessary to study the effect of stations that may be entirely shut down during part of a period, only being operated during the peak, or in case of emergency.

A close study of the line operation is also necessary, as the relay scheme and operating scheme must go hand in hand, for neither can obtain the best results independently. One changed method of operation may destroy the effectiveness a well-designed relay scheme, whereas some other change in operation would result in more effective protection. Relays that require time and current settings for selectivity cannot always be set to meet every possible operating condition. Therefore settings that fit the normal conditions and as many of the emergency variable conditions as possible should be used. Likewise operation rules cannot always be made to fit the relay schemes, but if the operators are kept advised as to the field that the scheme covers, they will, where possible, pick out emergency connections and make other operating changes to fit in this field. Also if informed of these conditions, when it is necessary to go outside of the limit of the relay scheme the operators will know what to expect and will be able more quickly to locate any trouble or faults. In general, for selective relay protection it is best to operate the system with all lines in service and to eliminate, insofar as possible, special conditions such as split busses.

Whether it is necessary to take into account the synchronous load on the system depends on its relative capacity with regard to the total generating capacity. Motor-generators and synchronous converters that have an interconnected d-c. system tending to keep up their speed have a much greater effect than synchronous condensers that have only their inertia to attempt to maintain their speed.

RELAY APPLICATION

Relays are applied to transmission systems in order that customers may be given continuous service and that the revenue lost by the power company through interruptions may be a minimum. Protection supplied, to apparatus is of secondary importance and is a field which is not covered by this paper, although properly designed transmission relay schemes correctly applied are a distinct advantage in this respect, as the strains on apparatus are reduced by the time limitation imposed by the line relays.

Each relay system and each piece of apparatus entering into the make-up of the system has definite characteristics and limitations. In a like manner each transmission system, and in fact each line making up that system, has definite characteristics which distinguish it from other lines or systems. Satisfactory applications cannot be made without complete knowledge of the characteristics of the protective relays and associated apparatus and of the transmission system and lines to which the applications are to be made. Adequate relay schemes have been condemned through the failure of the application engineer to recognize and weigh all of the factors involved. In some cases difficulty is experienced in isolating or evaluating a factor until after an installation is in service, or an error is made in application, but careful analysis of operating records, supplemented when necessary by tests, will reveal the weakness in the scheme or the value of the factor which was omitted from consideration with the result that the installation may then be corrected or a more suitable scheme installed. At least one case of this type was reported by an operating company and subsequent results show that the diagnosis, made after a number of faulty operations, was correct.

There is a tendency at times, to complicate installations by the use of auxiliary devices to make relays perform operations which are the functions of the operators. The attempt to endow protective relays with judgment in addition to the usual function of discrimination leads to disastrous results through the failure of the auxiliaries to function properly. Maintenance charges are high on such installations, reliability is sacrificed to intricacy, and the service rendered is not commensurate with the cost.

Many relay schemes are, of a necessity, complicated but the trend should be toward simplicity and, other things being equal, the simplest installation selected.

One other item which is frequently overlooked is the phasing out of installations before cutting into service. This work can be done most intelligently by the engineer in charge of relay applications, or at least under his supervision. One company reports that it is its practise to have three independent checks on phasing made before cutting an installation into service. These checks are made under load conditions, first, by the engineer in charge of construction or his representative; second, by the testing department; and third, by the engineer in charge of protection, or his representative. In this way the work of the various departments is properly coordinated.

GENERAL PRACTISE IN RELAY SETTINGS AND TESTS

Emphasis should be placed upon the necessity of having one person in authority to determine what current and time settings shall be given to all important relays on the system. The testing and adjusting of the relays, after the settings have been determined, need not be so centralized but it seems to be the usual practise and, as outlined in a preceding paragraph, would appear desirable.

The man who determines the relay settings must be in close touch with the operating department so as to be acquainted with all of the operating conditions, weak spots in the system, such as inadequate circuit breakers and lines, and important loads which must be given preference when laying out the protective scheme. Usually the relay man is a member of the engineering department or, less frequently, of the operating department. Another method is to handle protection of the system through a committee consisting of one or more members from each of the interested departments. The personnel of such a committee will depend to a great extent upon the organization of the company.

The use of inaccurate current transformers such as the low-ratio through or bushing type, may necessitate special consideration when determining the current settings of relays, but after the relays are installed no difficulty need be encountered in testing the assembled equipment if the method mentioned in the previous paper is followed. In this connection, it may be well to point out that even with transformers of these types, the phase angle error will seldom prevent the use of directional relays.

Potential transformers do not, as a rule, enter the problem of setting relays except in cases where the phase relation between the high-tension line and the relay potential bus is shifted 30 degrees by the introduction of star-delta transformers which may make it necessary to adopt some expedient to secure the proper phase relation and voltage value for directional relays.

Practically all circuit breakers now being manufactured will open the circuit in less than 0.25 second so successive relays may be given a time difference of 0.5 second and thus allow a wide margin of safety. Smaller time intervals are being used in a few cases but this is not usually advisable unless each circuit breaker has been individually calibrated and is given frequent inspection. The increasing attention which is being given to the problem of automatic sectionalizing is emphasizing the importance of careful adjustment and inspection of the circuit breakers.

Many companies test their important relays with a cycle counter at the time of installation and thereafter at intervals of six months or a year depending upon the importance of the service and the location of the relay. This test is made regardless of the care and accuracy of the factory calibration because of the very nature of the installation which places considerable responsibility on a single piece of apparatus which will receive little attention after it is once installed and therefore should be thoroughly tested and verified before it is placed in service. Furthermore, a test of the relay with current makes certain that it is in good mechanical condition and if the current is applied near the current transformers the condition of the wiring is also verified.

Notes on Foreign Practise

A larger proportion of the transmission systems in European countries consist of closely spaced conductors than is common practise in America, as the density of population, relatively short distances and lower voltages make this form of transmission more desirable. As a result, differential current schemes of protection have received more attention and a number of principles utilized which are entirely different from those found in American practise.

In England, in particular, more attention seems to have been given to differential schemes than any other form of relay protective equipment, and the development of over-current and directional relays has lagged accordingly. Originally, pilot-wire protection was preferred, then split-conductor, and at present the preference seems to be returning to pilot wire. Methods of eliminating capacity effects in pilot wires and the relatively cheaper first cost as compared with the split conductor, would account for the reversion. The English schemes lead in diversity of principles employed for selecting the faulty line but in methods of application and the development of devices, American practise seems to be superior.

The influence of developments in the art in each country is beginning to be felt in the other country and it is to be hoped that some of the basic principles established in England will be adopted in America, as the English engineers have already adopted some of the American schemes. In this connection it is interesting to find that one company in the Far East, operating under the supervision of an English engineer, installed during the recent war, the American adaptation of the split-conductor scheme for closely spaced conductors. The special oil circuit breaker consisting of six poles (two in each phase) to clear trouble on end faults as used in English practise, was not obtainable, so, after visiting the American installations, the modified scheme was adopted consisting of standard three pole circuit breakers and end reactors to assist in clearing end faults.

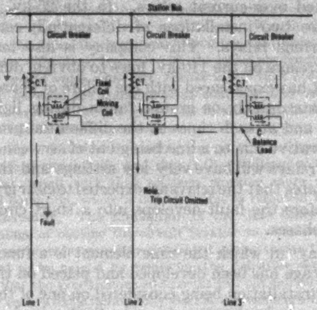

Fig. 26—A Typical Differential Scheme as Used in English Practise

Many of the English schemes require the use of special conductors and their use is not economically justified except in special cases, because of the large capital expenditure required to obtain only slightly better protection than is obtainable by other and cheaper means. There are, however, a number of other schemes which do not use special conductors and which are desirable because of the stability obtainable with very low settings. A typical example of this form of protection applicable only to outgoing lines is shown in the single line diagram, Fig. 26.[4]

The relays employed in this scheme are the directional current type having a fixed coil and a movable coil. Under normal operating conditions the current from each transformer circulates through the fixed coil of its relay. The moving coil connected to the balance lead is not excited. If the faulty line 1, carries the greatest current as would be the case in an installation on three parallel lines, the balance of the secondary circuit is disturbed, the residual current flowing through the balance lead and moving coils in such directions as to operate the relay with its fixed coil connected to the faulty line and restrain the other relays. The greater discrimination obtained by introducing a definite restraint upon relays connected to healthy lines during abnormal conditions is a principle which should be given consideration in this country for both transmission line and apparatus protection.

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[4] Automatic Protective Devices for Alternating Current System. A. E. McColl. Jour. Inst. of Elec. Eng., July 1920 page 525.

In other countries also, recognition is being given to the advantages of differential protection. In Spain there is a transmission system supplying a territory of some 16,000 sq. km. (6177.6 sq. mi.) with a load of 152,700 kw. in 1921 consisting of a network of 110-kv. and 25-kv. lines. On the 110-kv. system there are nine installations of differentially-connected directional relays and two installations of differentially-connected over-current relays. In the 25-kv. system there are two installations of differentially-connected over-current relays. This company is also installing ground relays on the 110-kv. lines to obviate difficulties which it has experienced with the failure of phase relays to operate quickly on ground faults during light load periods and at such times as the differential protection is inoperative due to a line being out of service. These ground relays will have very low settings and the company states that the relays are expected to clear grounded lines before the fault develops into a short circuit between phases.

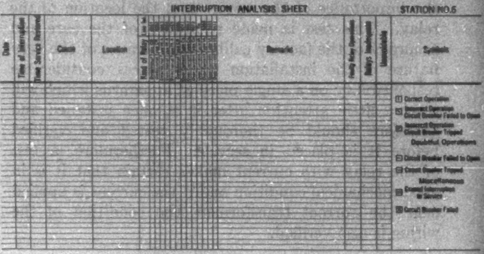
A relay[5] in which the time element is a function of line voltage has been developed and placed on the market, an installation being considered on one of the high-voltage, single-phase systems in Switzerland. These relays have a potential coil restraining element, the amount of restraint being directly proportional to the line distance between the fault and the relay, thus, those relays nearest the fault will select the proper line as they are subject to the minimum restraint.

OPERATING RECORDS

There is one suggestion which may well be emphasized and which followed, will undoubtedly increase the value of the work of the committee besides increasing its efficiency and making the work less burdensome. In analyzing the replies from the various reporting companies it was found that some were much more comprehensive than others. From further analysis it became evident that the most difficult ones were from companies who apparently did not have any *good method* of keeping a complete record of interruptions and relay operations. Companies who kept such records were able to answer, definitely, questions to which others could give only vague replies. This lack of definite information was less noticeable in the descriptions of equipment and schemes than in operating results. This would seem to indicate that each company thoroughly investigates the apparatus and schemes before installation and keeps a record of the installation, but that, in a great many cases, adequate operating records are not kept. The engineer in charge of the relay system may know, in a general way, the results that he is getting from his protective equipment but unless a record, giving each detail of operation of the apparatus involved, is kept it will be difficult to determine the effectiveness and next to impossible to make a report showing whether satisfactory results are being obtained from any scheme.

It has been the experience of some of the largest companies in the country that such a record is invaluable in determining the worth of various protective schemes and in choosing the method of protecting new lines. Since beginning to record and compare operating results it has been found possible to determine without difficulty the cause for a great many incorrect operations and to increase the efficiency of protection.

It is the operating data which determine the value of any protective scheme and that such data may be more easily collected and analyzed, the Protective Devices Committee is prompted to suggest a form of Interruption Analysis Sheet, as shown in Fig. 27. A form similar to this has been used with very satisfactory results by several operating companies.



INTERRUPTION ANALYSIS SHEET STATION NO. 5

Date	Time of Interruption	Time Service Restored	Cause	Location	Kind of Relay	Remarks	Faulty Relay Operation	Relays Inadequate	Unavoidable	Symbols

Correct Operation
Incorrect Operation Circuit Breaker Failed to Open
Incorrect Operation Circuit Breaker Tripped
Doubtful Operations
Circuit Breaker Failed to Open
Circuit Breaker Tripped
Miscellaneous
Caused Interruption to Service
Circuit Breaker Failed

FIG. 27—SUGGESTED FORM FOR RECORDING INTERRUPTIONS AND RELAY OPERATIONS

An examination of this form will show that provision is made for recording every detail of the Interruption and relay operation. Unusual features which cannot conveniently be classified may be entered under the heading of "Remarks". A sheet is made up for each station and a cross index with other stations which may be involved can be obtained by referring to them under "Remarks". Each incoming and outgoing feeder is identified with the type of relay by which it is protected, and space is provided for recording and conclusions drawn from the analysis; that is, whether an interruption may have been caused from faulty relay operation, inadequate relay protection or other cause, or whether it was unavoidable.

The form shown is, of course, subject to modifications to meet various conditions but it is felt that an Interruption Analysis Sheet, embodying these essential features will permit the keeping of all the details of operating records in a compact and easily comparable form.

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[5] *E. T. Z.* No. 50, 1919 and January 16, 1920.

It is, therefore, recommended that operating engineers give this suggestion serious consideration, as it is of greatest importance that the operating companies know exactly what results are being obtained in order that such schemes as do not give adequate protection may be replaced by more effective schemes, thus stimulating progress and weeding out such schemes and devices as have not proven satisfactory.

It is to be hoped that the foregoing descriptions of schemes and practises in transmission line relay protection will result in a clearer understanding among engineers of the present state of the art. It is the purpose of the series of papers on Protective Relays to keep operating engineers informed as to what is available for meeting each and every operating requirement and to keep designing engineers in close touch with the problems met in the operating field. In order to fulfill this purpose the Protective Devices Committee must have the full cooperation of both the operating and the designing engineers. The cooperation which has been given and the interest which has been shown in the work have been very gratifying.

Discussion

E. R. Stauffacher: The nomenclature and classification of various relays and the acceptance of this nomenclature by the Standards Committee of the A. I. E. E. is a distinct step forward. Relays are assuming more and more importance in their application to central station systems, not only where the load is largely concentrated, but where it is spread over a large territory covering, for example, one-half of a large state. In both cases it is quite necessary that the defective section of such a system be localized, even though in some cases it may take a couple of days for a patrolman to go over the line which is in trouble. The big job is to drop the defective section as soon as possible before it upsets the remainder of the system.

I have referred in a former discussion, to the difference in the Pacific Coast conditions as compared with the eastern conditions and I wish to mention now that the lines are quite long in some cases; 240 miles in our particular case being the longest line. We have only comparatively recently begun the application of modern relays to our system, and are just beginning to learn something of their fine points as well as their limitations.

We have a peculiar condition with our 150-kv. Big Creek line. Mysterious flashovers occur that are not associated with any particular kind of weather, any part of the day, nor any part of the night. It appears to be a hopeless task to find a reason for the flashovers and to eliminate them, so the next thing to do is to get rid of the defective section in our most important transmission line, even though we have to go counter to the opinion of some of the more conservative engineers. It has been decided, therefore, that when the line is changed to 220-kv. operation that the current balanced method will be used for eliminating defective sections. We are only planning to eliminate the first defective section. If the first section should go out on account of trouble and the second section should also get into trouble later, this second section will not be isolated by relays applied to the transmission line, but will be handled by means of a field-killing device on the generators at the power house. Current flowing to ground will operate certain contact-making ammeters which will cause a motor attached to an auxiliary "trouble" rheostat to cut resistance in the generator field as long as current is flowing to ground; and as soon as the ground current ceases to flow the contact-making ammeter will reverse its contacts and the motor will reverse, bringing the generators up to full voltage. Under present conditions, this operation is performed by hand and takes an average of approximately 15 seconds to handle a flashover. There it not much difficulty in handling a flashover manually when one or two power plants only, located two hundred-fifty miles away from the load are operating, but when we have three, four, and ultimately as many as eight power plants attached to one or two transmission lines, it will be necessary to have some automatic means of lowering the voltage in case the second transmission line gets in trouble.

Mr. Hester has emphasized the necessity of the manufacturers and the operating men getting closer together and has pointed out the fact that the operating men misapply a relay occasionally and I think that point is very well taken. We, in the west, located so far from the large manufacturing companies, find it particularly difficult to keep up with the latest applications, so I certainly would voice what Mr. Hester says—that a closer cooperation between the manufacturing company and the operating engineer would help a great deal in securing the best possible application of relay protection.

R. Bailey: I notice, in reading the paper, one thing which is emphasized throughout, and that is the tendency to do away to a great extent with time settings, working more with the balanced condition, where a defective line is removed from the system instantly. The elimination of the time delay has the disadvantage of causing the circuit breaker to open before the short-circuit current can decrease but it seems to me there is a good deal to be gained by removing the defective section so quickly that the synchronous equipment will not fall out of step. In many cases a cable failure may start as a breakdown to ground and the use of time delay relays may allow this fault to develop into a severe short circuit before the oil circuit breaker opens, thus increasing the duty required of the breaker and leading possibly to a system disturbance.

Most of the schemes presented, I believe, are open to the objection that they do not protect against the failure of a station bus, but it looks to me as if this is not a serious objection, as there have not been many cases of bus failure, due no doubt to the precautions taken to obtain liberal design and sturdy construction of busses.

Most of the differential or current balance schemes are applicable where three or four lines are operated in parallel, but where it is a case of operating just two lines in this manner, the schemes do not work out very well. This is a real objection because on a number of systems it is the practise to operate just two lines on the same bus section rather than three or four in order to limit short-circuit currents. While it is true you can get better continuity of service with three or four lines in parallel, the magnitude of short-circuit currents may prohibit this practise. Then, again, the differential scheme usually involves interconnection of transformer secondary leads, which is not in accordance with the idea of completely sectionalizing equipment to prevent the communication of trouble from one line to another.

Most substations are provided with double busses, which further complicates the application of differential relay protective systems, and in some instances make it inadvisable to use a scheme of this sort.

In one place in the paper a scheme is suggested which involves grounding one phase of the system at the time of a ground on another phase of the same line in order to cause the excess current relays to operate. While this will no doubt separate the line from the system it may cause a serious disturbance and it would therefore appear to be advisable to provide other means for isolating such a line.

In closing I wish to emphasize the need for simplicity of all relay protective systems. A number of them which will theoretically, do the work intended are rather complicated and therefore difficult to keep in condition, resulting possibly in failure to function. It is rather unfortunate that in some cases such systems are not given more care in the design and installation, and in their maintenance afterwards. This condition seems to be due to the fact it is not realized that the relay protective systems are far more important than the investment involved would indicate.

Paul Ackerman: Relay protection is a wholly defensive measure and does not appear to produce any revenue. As a result it is usually very difficult to requisition the necessary money for such expenditures. Yet there is nothing more important than an effective relay protection to assure safety to a power system and to avoid expensive tie-ups to industries and disastrous destruction to power companies' properties.

Today, relay engineering is still about in the same stage as circuit breaker engineering was some ten years ago. In those days the size of a circuit breaker to be chosen and the money to be spent was determined by the importance or unimportance of the respective new feeder. Today, we fully realize that the oil switch to be chosen depends entirely on the main system to which the respective feeder will be connected.

Relay protection is mostly handled in a fashion similar to that in which circuit breakers were chosen some years back, the feeder to be protected only being considered. Yet an effective relay protection is possible only if in each case the main system as well as the respective feeder are given careful consideration.

Regarding the differential current schemes described in the paper, I am gratified to see that this principle has received general consideration within the last few years.

It was as far back as 1912 when I conceived of the scheme illustrated in Fig. 4, and ever since I have been working along similar lines despite great opposition.

The objections then raised were the same as those mentioned in the paper, that is, complication of wiring and interconnection of current transformer secondaries of different lines. The best proof that these objections are not very serious lies in the fact that those who raised the greatest objections originally are today the most ardent supporters of these protective schemes.

There is no doubt that all differential current schemes are complicated in wiring, but it must be remembered that wiring connections are made once only and if properly made are permanent and safe so that no trouble should be experienced from this cause. The relays themselves on the other hand, can be made of such elementary construction that they are usually much safer than the more complicated time-limit over-current or directional relays

The checking of phase relations is usually much simpler and more definite on differential current schemes than on directional relays.

The paper mentions also as one objection of the differential current scheme the fact that they require several relay contacts in series. In this respect, it may be pointed out that no fear from this cause need be entertained as long as the relays are of simple structure. The best proof of this is to be found in the fact that of the several hundred relay actions of the different schemes illustrated in Figs. 4 to 7, there is not a single failure which could be attributed to this cause.

From my experience, it is usually safer to adopt a scheme with simple relays and several contacts in series rather than reduce the number of contacts at the expense of a more complicated relay. Such complication in the relay structure is invariably required if a similar effect is to be obtained. A comparison of Fig. 1 and 7a is an example of this kind. The two schemes are fundamentally the same except that Fig. 7 attains the results by two relays with the contacts in series to each other whereas in Fig. 1 a relay has been developed which requires only one contact, combining the two functions cleverly in one relay, thus, however complicating the relay structure.

The paper mentions another drawback of differential current schemes being the fact that they are unable to take care of bus bar short circuits and that for this purpose additional overload protection is required. In this respect I might say that the power companies will have to realize that they will never be able to obtain a relay which can perform all the required functions and accordingly they will have to accustom themselves that several different type relays will have to be installed on the same switches in order to cover all possible conditions. I might mention as an example that I have come across cases where I considered it essential to install as many as 5 or 6 different types of relays on the same line.

With respect to the various differential current schemes, illustrated in Figs. 1, 3 and 7 used for double line protection, it will be noticed that they are based on the same fundamental facts but that the means employed are different.

Schemes shown in Figs. 3 and 7 report provision of blocking of the protection of the remaining line after one line has opened. The description for Fig. 1 leaves the impression that no such blocking is provided. If such is the case, I would point out that under certain conditions where the current setting of the relays must be made very low, this omission may lead to trouble.

It must also be clearly understood that the various differential current schemes have certain limitations which have to be kept well in mind.

Open-circuited phases for instance, have the tendency of tripping the wrong line unless the relays are set higher than the total load fed over the two lines.

There are also conditions arising where an arc sometimes clears after one line end has been opened. Under such condition, the danger exists again that the other end of the other line may open wrongly and thus cause a total interruption. This danger exists wherever the recovery current may be heavy and where the relays have comparatively low current setting.

These limitations are of little consequence on underground systems where open circuits and self extinction of arcs are very rare. Also on copper lines where cable breaks are rare or on short overhead lines of pin type construction where arc extinction is less to be feared, little trouble should be experienced with differential current protection.

The conditions are somewhat different on long overhead lines, particularly with aluminum cables where breaks are more likely to happen, and where arc extinction is more pronounced.

The above is clearly indicated by the fact that the protective scheme as per Fig. 7 has given practically 100 per cent effectiveness on single line shorts on a 90,000-volt pin type copper line whereas the effectiveness seems only to be about 80 per cent on some other lines of aluminum and suspension construction.

Regarding the differential current protection for 3 and more lines as illustrated in Figs. 4, 5 and 6, I would like to point out the effectiveness and simplicity of this scheme. The simplicity lies chiefly in the fact that relays of the simplest type can be used and that no blocking relays are required. The wiring, though somewhat complicated, can be made fairly simple, particularly on 3-feeder protection, especially if scheme 6c is used. The scheme adapts itself particularly to underground distribution where substations are very often fed over three or more cables. In such cases, it is usually very rare that operation is maintained with only two, or one feeder, or under any such condition one is usually satisfied to have a protection on two feeders which at least does not operate wrongly on through short circuit, while mostly it may be acceptable to cause an interruption under such operating conditions in case of trouble in one of the two cables.

For any such case, this scheme is splendidly adapted and decidedly advantageous compared with scheme, Fig. 2, as to cost as well as simplicity of relay equipment.

Regarding the merits of directional relays combined with overcurrent relays, it is quite evident that considerable improvements have been made on the directional relays, making them operative down to very low voltage. Modern connections also leave the directional relay effective on single-phase shorts. Still the facts remain that the arrangement should be used cautiously and reluctantly on higher voltage systems, and particularly overhead lines since under such conditions single-phase short circuits often develop rapidly into three-phase short circuits, thus making the action of the directional relay doubtful unless the arrangement is such that sufficient voltage is left on the relays to operate effectively.

No doubt for certain conditions there are no other means available at the present time. The best proof of the limitation of this principle, however, can be seen in the fact that the differential current schemes have been able to make such rapid headway within the past few years.

Regarding the split-conductor principle and the pilot wire principle, I must confess that I have no sympathy with these principles as far as their application for transmission and distribution lines are concerned, except possibly for very short runs.

Both principles in themselves are ideal in view of the fact of clearing both ends of the faulty apparatus simultaneously. For generator and transformer protection they are ideal and deserve more general use.

For line protection, however, the complication, the hazard and the cost are becoming excessive as soon as the lines or cables exceed one mile in length and it is my firm belief that under such conditions they are not able to compete with the differential current schemes, with the exception of very special cases.

The advantage claimed for the split-conductor and pilot wire scheme of having no interconnection between adjacent lines is in my opinion far more than counteracted by the complication and hazard introduced in the split-conductor cable and in the pilot wires respectively.

It is also claimed that the split-conductor or pilot wire schemes are able to limit the damage on cables and the effect of the disturbance on the system because they are supposed to clear the fault before a complete breakdown has occurred. I believe that this view is erroneous. I cannot conceive of any fault, after having developed sufficient current to operate even the most sensitive relay to take longer than 0.3 sec., which is the rupture time of the oil switch, until it has completely broken down. In my opinion, a dead short circuit is developed within a small fraction of a second after any appreciable current has started to flow through the fault, so that the short in practically any case should be completely developed before the oil switch had a chance to open, even if tripped by the most sensitive relay. The limited damage, therefore, in my opinion is caused by the rapid clearance of the short by the quick acting breaker but not by clearing the short premature to the complete breakdown.

Very similar results are observed from the action of differential current protection; flash-overs on overhead lines, cleared by the differential current protection, never damage the insulator sufficiently to disable the line permanently unless the insulator punctures. Cable faults are cleared without undue damage but just sufficient to permit detection.

Split-conductor and pilot wire schemes, therefore, are in no way superior to differential current schemes in that respect.

With respect to the ground selector, I would like to comment on one statement of the report. The paper mentions that the chief disadvantage of the ground selector would appear to be the loss of the advantage of the permanently grounded system. In my opinion, the reverse of this statement is rather correct.

Ungrounded neutral has always been found preferable in many respects, chiefly in regard to transformer connection and the total number of interruptions. The chief drawback was the difficulty of locating grounded feeders and the damaging effect caused by lasting grounds.

The preference given to grounded neutrals is entirely due to a desire to overcome the above serious trouble. This is true at least for voltages up to 60,000 volts.

The ground selector performs on the ungrounded system the same duty for which the grounded neutral has been introduced but with the benefit of being able to retain the advantages obtained from an ungrounded system.

The ungrounded system, therefore, equipped with a ground selector, combines in my opinion the advantages of the ungrounded and grounded system without, however, having any of the disadvantages of either system. The results on the 12,000-volt Toronto distribution show particularly how great a number of self-clearing grounds are given a chance to clear without any disturbance whatever, whereas with a grounded neutral each one of the self clearing grounds would have meant a voltage disturbance and a partial interruption.

Regarding the keeping of records on the functioning of relays, it cannot sufficiently be emphasized that it is very essential to collect as exhaustive information as possible. It is very important, however, to try to obtain the correct information.

For instance, a total interruption on a double line system protected by a double line protection can be caused either by a double line short circuit or by wrong relay action.

Past experience has made the operating man so suspicious of wrong relay actions that he is inclined to dismiss any such case without further investigation by considering it simply a wrong relay action, whereas possibly the relays were acting to the best of their ability.

Short circuits across two lines built on the same tower line or in close vicinity on the same right-of-way are not as unusual as thought. Such possibilities must be given careful consideration before blaming the relays.

On the other hand, each case of wrong relay action must be carefully studied to find the reason for such behavior. Only thus will it be possible to gradually develop the necessary improvements.

In closing, I wish to emphasize that we must not be lured into the belief that we are about to enter the stage where protective schemes are available to cover all the various conditions. On the contrary, we have only just started to realize that our old protective schemes are obsolete. Much hard work will still have to be done to develop the standard of perfection which will be required on systems such as the super-power scheme.

It must also be remembered that the various protective relays of a system have to be properly coordinated and that this can only be done by having this matter centralized in the hands of one man who will be able to concentrate his whole thought on this one problem.

It is also essential that each system be studied on its own merits, also each individual problem. To copy other companies' practise, without careful analysis of the fitness to the conditions under consideration, may lead to very disastrous results since a scheme may be fully effective in one system and a failure in another one. The work of the Relay Committee acquainting us with different schemes must be accepted with that fact in view as otherwise the Committee reports may become misleading.

E. M. Wood: Possibly you may be interested in a description of some rather unique features of relay protection we have in the Queenston power house. You will notice from Mr. Gaby's paper that we have used the current differential relay system to a large extent to protect the busses and other equipment in the station. We have found in some other power houses that we have trouble quite frequently on the busses and it was considered necessary to protect them.

The scheme which is used can be shown in diagram (See Fig. 1). We have this on the generator, on the 12-kv. bus, and high-tension bus, and on the transformer bank. The relays used are plunger type and give quick operation in order to cut out defective equipment as quickly as possible, and if possible leave the rest in. On the outgoing lines, we have the inverse-time overload induction type of relay. It is our intention to use current differential protection on parallel outgoing lines to the same substation.

A study of the plant characteristics seemed to indicate that there would be a danger, under certain conditions of partial rejection of load, that the machines would drift apart. We have therefore used inverse-time overload relays between bus sections.

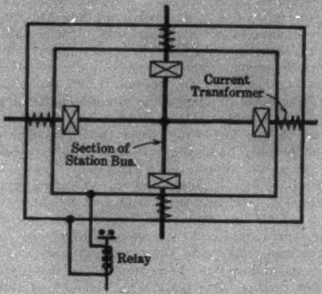

FIG. 1

In the case of the current differential relay there is always a certain suspicion that possibly it will operate when it should not. In order to overcome that, we have taken considerable pains to get current transformers that maintain their ratio. Secondary connections between current transformers are kept short and the long runs to the control arm carry only the residual current.

There is also installed a reverse-current relay of the spring restrained instantaneous three-element induction type on each generator intended to trip out in case of careless synchronizing. As our differential groups of current transformers do not include the delta bus and low-tension terminals on the transformers we have installed a ground relay to trip in case of ground on that section of the wiring. To date the relays today have operated as they were intended to operate, and have not operated when they were not intended to do so.

R. N. Conwell: In the announcement of this paper the statement was made that "relays do not constitute a profitable business." Undoubtedly, the writer of that phase had in mind development and manufacture of relays. The question, "Do relays constitute a profitable business for power companies?" may be answered just as definitely if accurate interruption and relay operation records are kept.

The question has been answered by one operating company and it is hoped that the presentation of the results of the analysis by which the answer was obtained, will lead other companies to make similar analysis.

The interruption and relay operation records for a five-year period on thirteen typical substations or about 15 per cent of the total number of substations in the system were examined and all interruptions which were unavoidable or not chargeable to relay protection eliminated. These interruptions included those due to operating mistakes, failure of oil circuit breakers, bus short circuits, failure of control or excitation sources and similar causes.

The relay protection in 1917 was no better nor worse than that to be found on many systems today. Intensive relay work in the field was started in the spring of 1918. The table shows the results of this work.

NUMBER OF AVOIDABLE INTERRUPTIONS

Substation	1917	1918	1919	1920	1921
A	26	7	9	4	0
B	15	6	4	1	0
C	8	4	3	3	0
D	7	3	1	0	0
E	17	12	3	1	1
F	35	37	9	12*	6
G	26	7	8	2	0
H	22	21	7	10*	2
I	18	41	9	16*	3
J	23	8	8	6	0
K	11	0	2	0	0
L	48	23	5	12*	0
M	15	3	5	3	0
Total interruptions	270	171	73	70	21
Total cases of trouble	288	302	185	212	130
Interruptions per case of trouble	.94	.57	.39	.33	.16
Lost revenue	$8500	..	..	..	$150

*Increase due to the most severe lightning season in the history of the company.

Capital Expenditure for Improved protection	$25,000.00	
Fixed charges at 15%	3,750.00	
Engineering, maintenance and testing	4,300.00	
Annual charge (13 substations)	$8,050.00	
Recovered Revenue basis for 1917-1921 figures		$8350.00
Annual profit		$300.00

On the basis of these figures, relay installations in this company "do constitute a profitable business" for in addition to a small cash dividend, they pay a much larger additional dividend in the reduction of damage to apparatus and equipment, and the increase in the good will of actual and prospective customers, by insuring continuity of service.

There is an interesting point in connection with Mr. Ackerman's discussion on the question of the grounded neutral. On this particular system, which consists of 13,000 and 26,000-volt lines, covering quite a considerable territory, the neutral was grounded in November 1918, and you will note the decrease of the cases with trouble after the grounding of the neutral, I think that this decrease is strictly chargeable to the grounding of the neutral.

A. H. Sweetnam: One of the larger central station companies has made during the past year rather extensive application of power unidirectional relays. The system so protected consists largely of multiple lines, supplying a number of substations in series.

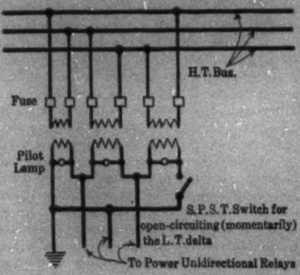
H.T. Bus.
Fuse
Pilot Lamp
S.P.S.T. Switch for open-circuiting (momentarily) the L.T. delta
To Power Unidirectional Relays

FIG. 2

There have been two cases of incorrect operation—that is, the unidirectional relays in one station have operated when the fault (a cable failure) was found beyond the station in which the relay operation occurred. In each case it was later found that one potential transformer fuse was blown resulting in changed relation between current and potential in the individual relays.

To avoid the probability of a repetition of such incorrect performance it was suggested to the manufacturer that three potential transformers be operated in closed delta with six primary fuses. The reply advised that this plan would be entirely feasible but that no difficulty would be experienced if a change were made to the fuse supplied by this particular manufacturer.

Notwithstanding this recommendation, the practise of this company now contemplates the use of three potential transformers and six primary fuses. It may be said that with six fuses the fatal day is only somewhat deferred, as with one fuse blown normal operation will be experienced until the second fuse fails. In this case, however, it is the practise to install a pilot lamp directly across the secondary of each potential transformer and install a s. p. s. t. switch in the low-tension delta connection. In this way at intervals such as may be considered advisable the continuity of primary fuses may be checked. (See Fig. 2.)

E. P. Peck: One of the biggest sources of trouble or failures in the operation of relays that we have experienced was not due to the relays themselves but due to the changes in the number of generators at the station. In the season of the year when there are high water periods most of the load is carried on the water power plants, and in the season of low water periods, most of the load is carried on the steam plants,—a condition which makes it almost impossible to make the proper relay application. This month we may be operating through our low period of the day with five machines in service in the hydro plant. The relays at the station and on the line must be set so that if one line is out of service, the other line is perfectly suitable for carrying the load without danger of an interruption. Next month, when the effect of the extremely high water that some of us have had has passed over, we may be operating only one, or at most two, generators in the hydro plant with most of the load carried by the steam plant. We cannot go over the system and reset all of our relays, consequently during cases of trouble our relays may not function. We have not had any advice from the relay engineers as to what to do to take care of that trouble.

Quite a number of our relays were set in a waterproof case out of doors to save wiring, and on these we had some particularly serious cases of relay failure. We found there was a little corrosion at some critical point, which caused the relay to fail. As a result of one or two cases of that kind, we have inaugurated a system of testing all relays, wiring and circuit breakers on the system that can possibly be tested, every week. Starting at twelve o'clock midnight on Saturday we test every circuit breaker on the system that can be tripped, by closing the relay contacts. That practise has caught a large number of things that would have caused trouble.

Near the end of the paper (Dec. JOURNAL), there is an interruption analysis sheet form given. I suggest that the name of the form be changed. A good many of us are keeping interruption analysis records now, and the interruption analysis records are very different from relay operation records. I think the better heading for that sheet would be "relay operating records" so that the stenographers will not always be pulling out the wrong report when you want the relay operating record.

W. H. Cole: Some four years ago I presented a paper at a meeting of the Institute on "The Experience of the Boston Edison Company with Balanced Protection," including our experience since 1913 with split-conductor cables. At that time our operating experience was rather limited, but at this date we can say that we have had an operating experience with split-conductor cables approximating 600 mile-years.

Everything brought out in the original paper regarding advantages and troubles incident to the use of these cables has been confirmed by more extensive experience in the last four years. All the favorable results have been continued. A great many of the doubtful relay actions have been cleared up, so that they are now considered normal and creditable.

As I analyze the situation, the principal disadvantage of split-conductor cable, or pilot-wire protection is the extra cost of construction and installation. These costs are admittedly high, but by many transmission engineers are considered to be well warranted. However, other protective schemes are being applied utilizing standard conductor lines with nearly the same advantages derived from split-conductor cables or pilot-wire schemes.

One serious objection to the use of split-conductor cables and pilot-wire schemes is that more duct space is required, which in many cases is vital, particularly in this country where the conduit system is standardized. It is obvious in the one case that split-conductor cables will be larger in diameter for a given capacity than standard cables, and in the other case pilot cables require duct space for their installation. Both systems of protection may be so arranged as to give ideal protection. The remaining question is what are they actually worth. The pilot-wire scheme has been improved very much in recent years and some of the original objections are eliminated, so that it may be said that it is coming back into its own, especially where no duct space is required, as in foreign practise where the pilot wire is laid in the open ground adjacent to the corresponding power cable.

One of the objections to the split-conductor raised abroad by large undertakings is that they usually lay a telephone cable with all power cable installations. In making up the telephone cable they find it convenient to combine the telephone conductors with pilot conductors in one cable, thus accomplishing two results with one cable. With the pilot-wire system of protection, as improved by Beard & Hunter, the combination of pilot wires and telephone wires has brought the total cost down to less than the cost of split-conductor construction. It seems that the whole question is one of economics, but engineers, who have ever had any large experience with split-conductor cables and pilot-wire schemes, generally agree that such systems are ideal.

O. C. Traver: Mr. Ackerman remarked in connection with the balanced schemes described for the protection of two parallel lines that if one of them should become accidentally open-circuited, it would have a tendency to open the other good line. While this is true there does not seem to be any material hardship resulting in practise. Furthermore, I believe the difficulty equally true of the other schemes mentioned by Mr. Ackerman as well as any balancing scheme when two lines are involved. In the same way when three lines are balanced practically any of the schemes described in the paper will properly take care of the matter in substantially the same manner as the one referred to by Mr. Ackerman.

I would like to add a word of caution in regard to the adjustment of relays used in the protection of systems with comparatively high resistance from neutral to ground. This warning is not intended in any way as an alarm, because in many cases the system has excellent possibilities. I know, however, that in a number of instances where ground current has been limited by resistance some of the resulting effects have been overlooked. Particularly in those cases where grounding transformers are located at some place other than the generating source, the intensities of the currents and the directions of power in case of grounds are entirely different from those resulting from phase to phase shorts. It, therefore, requires in most cases a complete separate analysis of the proper current and time settings and a very careful check on the question of directional relays.

H. T. Plumb: We will cite an instance where relays worked successfully. Five years ago relays were applied to the principal three-phase transmission line in Utah, operating at 130,000 volts and transmitting power from the plants in Idaho to Salt Lake City, 135 miles. Settings for the relays were worked out on a calculating table. These settings have not been changed in five years and the relays have given practically 100 per cent performance. There has been only one failure which is possibly chargeable to the relay. This is conclusive proof that these relays work.

With regard to the remarks of Mr. Stauffacher and his difficulty with curious short circuits this transmission line of which I speak was subject to very peculiar and many short circuits or flashovers between conductors. There were various theories for these failures. Some thought it might be due to the numerous swarms of small flies out of a nearby swamp. Others imagined many curious things were the cause of the trouble, but they never were sure of the cause. That was nine years ago and the trouble has not recurred. The most generally accepted theory is that the short circuits were caused by large birds, and that these birds did not leave evidence as to what had actually happened. It hardly seems possible that birds could receive the full line pressure, 130,000 volts, get away with a few burned feathers, and never leave anything else behind. In any event it seems that experience with the live wires taught these big birds how to alight on the towers, and to fold their wings so that they will not make a short circuit. Young birds might start the trouble again until they learn to be cautious.

L. N. Crichton: I would like to emphasize the question of simplicity in relay installations. It is easy if you work long enough and painstakingly enough to devise a scheme which will fit every requirement of a complicated system. But sometimes you find you have overlooked something, and other times you find that the scheme is so complicated that the men who operate it do not maintain it properly. In reading this report, it is important to remember that many operating companies have gotten over the trial period, and they no longer have any *trial* relays. One of the largest operating companies has 342 sections of lines protected by carefully designed relay schemes. This requires 1845 relays and 644 automatic circuit breakers. Bear in mind that this refers only to the devices for automatically sectionalizing the network and that these figures do not include the devices for protecting apparatus. This extensive relay system is justified not only by the improved service rendered, but also by the saving in copper which results from the close interconnection of feeders. Incidently, this system uses only the simplest schemes of relay connections. Now, by way of prophecy, the calculating table will become of less importance and the more or less laborious calculations now necessary to determine the proper relay settings will decrease as the relay art advances. Relays are being developed which will determine the location of short circuits and will operate only when the trouble is close to them. Elaborate calculations will not be necessary since each relay will make its own calculations when the trouble occurs.

It is possible that a description of such a relay will shortly be presented under the auspices of the Relay Sub-Committee.

W. R. Bullard: The description of the ground selector relay scheme of which Fig. 18 is a wiring diagram is particularly interesting because of its similarity to the operation of the so-called "arcing ground suppressor." However, the results accomplished by the latter are just the reverse of those described in this paper in that the arcing ground suppressor is used to ground the leg on which the fault occurs (instead of an opposite leg.) It therefore suppresses the arc and prevents it from producing a short circuit. Up to the present time the chief application of this type of apparatus has been in connection with distribution systems. A number of these suppressors are in actual use on such systems and have apparently been giving remarkably good service for several years. Their main advantage lies in their ability to eliminate the occurrence of a large number of short circuits and thereby reduce the number of outages. However, there is no apparent reason why the same scheme could not be applied to transmission. Such application would seem to be a more logical one than that of the scheme mentioned in this paper, since the effect would be to minimize the disturbances on the transmission system instead of deliberately creating them.

The authors lay particular stress upon the development of balanced protection for parallel lines. These schemes have a considerable number of advantages, the chief one being that of minimizing the necessity for a large number of selective time settings. However, one great disadvantage of some of these schemes lies in the necessity of keeping all the feeders of a group in service to secure the proper operation of the system. I am sorry that more space has not been given in this paper to detailed description of operating conditions under which these schemes have been used, and specific methods of over coming this difficulty.

Referring to the various schemes which have been developed for ground protection, the chief advantage of this form of protection lies in the ability in some cases to use extremely low time settings thereby disconnecting the faulty unit before a phase to phase short circuit has had time to develop. It is stated in the review preceding the paper that the application of these relays with regard to current and time settings is based on the same principles that apply to relays used for short-circuit protection. However, it should be noted that where two or more selective time settings are used, the purpose of the special protection is in danger of being defeated by the greater time taken to clear the fault. It would therefore appear that the only real solution to the problem in this case would be the combination of ground relays with other more expensive schemes, such as pilot wire and other such systems.

S. W. Mauger: Too little attention was formerly paid to the subject of protection of lines both by designers and operators, the former not being able to appreciate the requirements, until the operators awoke to the necessity of further study and placed the condition more clearly before the designers.

In many cases, relays were simply considered as auxiliary devices to cause circuit breakers to open in case of trouble. The broad subject of continuity of service was not thought of in connection with relays which indeed were thought of only as *interrupting* continuity.

Modern relays, although comparatively insignificant in themselves, when properly applied, make it possible to maintain continuity of service with stations interconnected to give maximum efficiency of conductors. This may result in some cases in the saving of thousands of dollars in investment, as the multiplying of circuits and the isolating of stations to avoid general shut downs is obviated.

As a result of the awakening to the real needs which were becoming more and more serious due to expanding systems, the manufacturers in cooperation with the operators went into the subject intensively and at considerable expense and they are now able to furnish relays to meet practically all conditions. There is still much work to do on the part of the manufacturers but they are alive to this fact.

Many operating companies are giving the matter serious attention, but it is feared that there are many more who are not and it is hoped that the relay paper under discussion will be earnestly studied by all operating companies. I would particularly stress the matter under the headings of "The Calculation of Short-Circuit Currents," "Relay Application," "General Practise in Relay Settings and Tests" and "Operating Records."

Power Development on the Colorado River

And its Relation to Irrigation and Flood Control

BY O. C. MERRILL

Executive Secretary, Federal Power Commission

Review of the Subject.*—The Colorado River drains an area of 250,000 square miles in the States of Wyoming, Colorado, Utah, Nevada and New Mexico, Arizona and California, and in the Mexican States of Sonora and Lower California. It is the third largest river basin in the United States and is fourth in volume of waters. The basin contains some five million acres of irrigable land and possibilities for power development exceeding six million horse power.*

The upper section of the river to the Utah-Arizona State line comprises 40 per cent of the basin, contains one-half of the irrigable land, supplies 87 per cent of the annual run-off, and could develop some two million horse power. Developments in this section, particularly storage, are likely to result in conflict between power and irrigation. The middle section from the Utah-Arizona line to the mouth of the Williams River comprises 35 per cent of the area, contains comparatively little irrigable land and supplies only 7 per cent of the annual run-off. This section, mainly in deep canyon, has a drop of about 3,000 feet and could produce four million horse power. The lower section with 25 per cent of the area of the basin has two and a quarter million acres of the best irrigable lands, provides 6 per cent of the run-off and has comparatively small power resources.

The most valuable lands in the basin are in the Imperial Valley, which, due to the fact that it is below sea-level and that the delta of the Colorado is very unstable, is constantly menaced by floods. The chief immediate problem on the river is, therefore, flood protection for this valley. Such protection can be secured by a storage reservoir either at the head or at the foot of the middle section. The latter site appears the more immediately available. The upper site would, however, afford adequate flood protection and give irrigation regulation for many years, and would, in addition, control the middle section for power development. The location of the primary storage on the river is an important matter and may determine the whole course of power development.

The rate of power development on the Colorado is a question of markets. With the exception of the mining district of Arizona, which might absorb 100,000 horse power, there is no present market in the basin sufficient to justify large-scale development. The most available outside market is Southern California which apparently could furnish sufficient demand for the initiation of power development on a considerable scale. Extension of such development in the future would involve interconnection, common control, and long-distance transmission.

Applications involving the Colorado and aggregating four and one-half million horse power are on file with the Federal Power Commission which has suspended action awaiting decisions upon collateral matters. The individual states have control over the appropriation of waters within their limits. To avoid the danger of future interstate litigation over water rights, the Colorado River Commission was created under authority of Act of Congress to work out a "compact" or "treaty" between the several States. It has not yet reached any conclusions. The stream also is international and irrigation rights in Mexico are involved. Finally, there is conflict over the question whether development shall be made by private capital or by the Government. These various conflicts of interests and of agencies are likely to postpone for a considerable time the solution of the problem of Colorado River development.

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INTRODUCTION

ONE of the most important and interesting of our present day engineering problems is the control and development of the Colorado River. Its interest and importance arise from the fact that it involves the irrigation of millions of acres of land, the production of millions of water horse power, and the protection from floods of millions of dollars of property values, and that it affects the general economic interests of seven of our States and two of the states of Mexico. It is of interest also in its political relations—using this term in its etymological, not its ordinary sense. Seven sovereign states claim in the use of the waters of the Colorado rights which in the aggregate may exceed its possibilities. Its waters can not be put to use without the sanction of the states in which the use is proposed and without the concurrent sanction of the Federal Government which owns the lands necessary for such use and which possesses a general control over the river from the fact that it is an international stream. It remains to be seen to what extent political considerations will modify engineering considerations in the solution of the problem.

The two main branches of the Colorado rise, the one in southwestern Wyoming, the other, in central Colorado. The length of the river from the headwaters of the Green to the Gulf of California is about 1750 miles. Its basin with an area of about 250,000 square miles includes practically all of Arizona, nearly one-half of Colorado and of Utah, one-fifth of Wyoming and of New Mexico, one-tenth of Nevada, and a narrow strip in California along the California-Arizona boundary. The Imperial Valley in California, though not topographically a part of the Colorado basin, should also be included because of its dependence upon the waters of the river and because of its intimate relation to the general problem of river control. Of the area of the basin some five million acres, or about one acre in 30, appear economically irrigable. Claims, however, have been made that there is a much larger amount of available irrigable land. The annual run-off of the

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river at Yuma averages about 18 million acre-feet. The average discharge is about 24,000 cubic feet per second, with variations from a minimum of 4000 second-feet to a maximum of 150,000 second-feet on the main river, and to 240,000 second-feet by inclusion of the Gila. The steep slope of the river and its large volume make it capable of producing some six million water horse power, or two-thirds as much as is developed in the United States today.

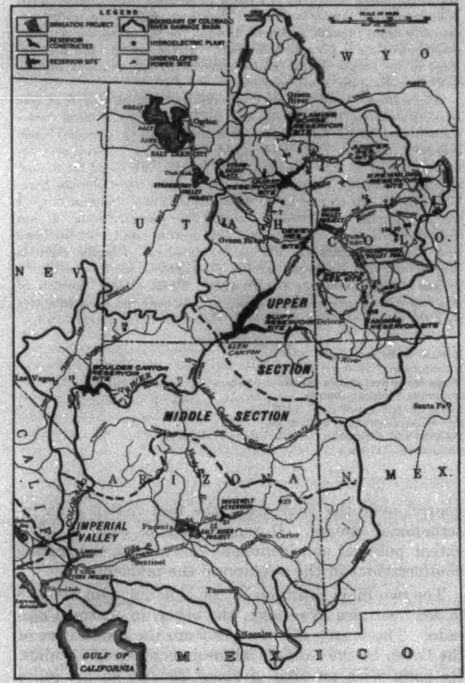

FIG. 1—COLORADO RIVER BASIN
Divided into sections.

THREE MAIN SECTIONS OF RIVER

A discussion of the general problems of the Colorado will be made clearer if we divide the river into three sections and consider the characteristics of these sections and their relations to each other. (See Fig. 1).

The upper section from the headwaters to the Utah-Arizona line, just below the mouth of the San Juan, comprises about 40 per cent of the area of the basin and affords about 87 per cent of the total run-off, or an average of about 15,000,000 acre-feet per annum. In this section are some 2,500,000 acres of irrigable land, one-half of the estimated total in the basin. It also has power possibilities aggregating 2,000,000 horse power. In this section, both upon the main stream and upon its tributaries, are many favorable reseorvir sites by means of which it would be practicable to regulate the flow of streams for irrigation within the section, or for power development both within the section and outside, or, if desirable, for flood control on the lower river. In so far as the tributaries are involved, these several uses would conflict to a considerable degree and only a careful study of the whole section could determine the best combination of uses. At the lower end of the section is the so-called Glen Canyon reservoir site which has an important bearing on all developments and uses of water below.

The middle section from the mouth of the San Juan to the mouth of the Williams comprises about 35 per cent of the area of the basin and supplies about 7 per cent of the annual run-off. There are no irrigable lands along the river in this section and only some 250,000 acres on the tributaries, none of which can be reached from the main river. In this section, however, there is a total drop of about 3000 feet, capable, if fully utilizing the average annual run-off entering the section, of producing 4,000,000 horse power. Except for the Boulder Canyon site near the lower end of the section, which would have no effect on the greater part of this section, there appear to be no storage sites capable of providing any considerable amount of seasonal storage. Dams erected for power development would be primarily for the purpose of concentrating head and of providing pondage for daily load regulation. Seasonal regulation would be dependent upon storage in the upper section.

The lower section from the mouth of the Williams River to the Gulf and including the drainage of the Gila and the Imperial and Coachella valleys in California, comprises some 25 per cent of the total area of the basin and furnishes about 6 per cent of the average annual run-off. Its power possibilities are relatively unimportant, but it contains some 2,250,000 acres of irrigable land, the most fertile and most valuable in the basin, of which a large part is periodically endangered by floods. There appear to be no reservoir sites of consequence below Boulder Canyon on the main river, but there are such sites on the Gila which could be used both for irrigation and for controlling the Gila floods.

Viewed solely from the physical standpoint, the upper section of the basin might have its primary development directed either toward irrigation or toward water power; or it might, as it probably will, have a combination of these two uses. On the other hand, the middle section, with the exception of storage below the mouth of the Virgin and of relatively small irrigable areas on the tributaries, is suitable only for power development. Equally clearly, the waters reaching the lower section should be devoted primarily if not exclusively to irrigation, and the storage sites should be employed for irrigation or flood control or both.

Flood Control Problem

The most immediately pressing problem on the Colorado River is flood control for the protection of the Imperial Valley in California. I shall not attempt, however, to discuss it in detail, but merely to present certain aspects of that problem in the relation they bear to water power and to a general plan of river development.

The Gulf of California originally extended northwesterly into what is now the State of California. The silt-laden water of the river gradually formed a delta cone extending across the Gulf, cutting off the northern end and deflecting the flow of the river to the south. The waters inclosed in the northern end evaporated leaving the depression known as Imperial Valley and the Salton Sea with its surface 250 feet below sea level. The silt-formed delta is unstable. The river is constantly depositing more sediment and shifting its channel back and forth over the flat ridge—some 30 feet above sea level—which forms the crest of the delta, and there is danger at each flood season that it may break northward into the Imperial Valley instead of continuing southward into the Gulf. The river did break through in 1905 and for more than a year and a half discharged into Salton Sea before it was turned back with great difficulty and expense into its old channel. The levees which were later built to protect the valley have several times been awash in periods of floods. It is necessary to raise them about a foot a year to keep pace with the rise of the river channel, and it is only a matter of time until the river will break through again unless steps are taken to control the floods. The situation is further complicated by the fact that the works for protecting the Imperial Valley are situated in Mexico. It is this condition of affairs which has placed primary emphasis on flood control in all plans for the development of the Colorado River.

Flood conditions on the lower Colorado may be caused either by high water on the main river or high water on the Gila. Flood conditions on the main river occur annually in the summer season, due to the melting of snows on the headwaters of the streams, and continue on the average from two to three months. The maximum flood from the main river in the years of record, 1902 to 1914, inclusive, has been 150,000 second-feet. The average mean monthly discharge during the three high months of May, June and July, for this same period of record has been: May, 42,600; June, 73,100; and July, 43,500 second-feet. While the floods from the Gila approach in magnitude those of the main river, they occur in the winter season, are caused by local rains, and are of short duration. Should it happen, however, by any combination of circumstances that extreme flood conditions on the Gila should coincide with similar conditions on the main river, a break through into the Imperial Valley would be almost inevitable.

On account of the volume of water involved it is apparent that protection from Colorado River floods can be had only by storage and by storage of large capacity. It is also apparent that full immunity from flood damages can be had only by storage on the Gila as well as storage on the Colorado. Since, however, storage on the Gila has only an indirect relation to the general problem of the Colorado River, it will be given no further consideration here.

There appear to be three practicable locations for flood control reservoirs of the capacity necessary. These are on the headwater tributaries, on the main river at Glen Canyon, and on the main river at Boulder Canyon. Storage on the headwaters would require several reservoirs and even though practicable from a purely flood-control standpoint, such a plan involves at least two serious objections. The operation of such reservoirs to meet the needs of the lower river would be likely to interfere to a considerable degree with the use of the waters for irrigation in the upper section and to a less degree for power development, depending upon their location and their manner of operation. If duplication of investment is to be avoided flood control reservoirs must also provide irrigation storage for the lower river. To operate for this purpose reservoirs located hundreds of miles above the lands to be irrigated would be an extremely difficult problem and would inevitably result in wastage of water and consequently in a storage capacity greater than would otherwise be necessary.

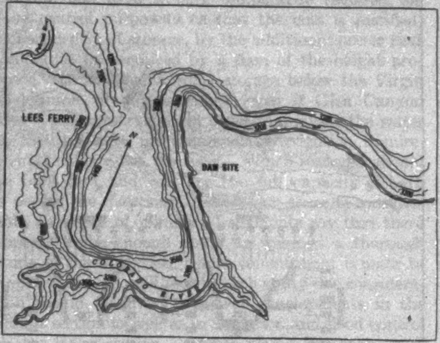

Fig. 2—Glen Canyon Dam Site
Site of proposed power development at Lees Ferry, Arizona.

Adequate storage for both flood control and irrigation could apparently be had at the Glen Canyon site at the Utah-Arizona line. (Fig. 2.) From an irrigation standpoint this site presents similar objections, though less in degree, to sites on the headwaters since the reservoirs would still be a considerable distance from the lands to be irrigated. From a flood-control standpoint, however, it appears adequate. It would intercept 87 per cent of the run-off of the basin, and would include every tributary of consequence above the Gila, except the Little Colorado. This stream is subject only to flash floods and enters the main river so far above the Imperial Valley that its floods can not be considered as dangerous. Storage at this point is of sufficient capacity to provide for power development and irrigation as well as for flood control, and hence would not interfere with, but would be a distinct aid to power development in the middle section.

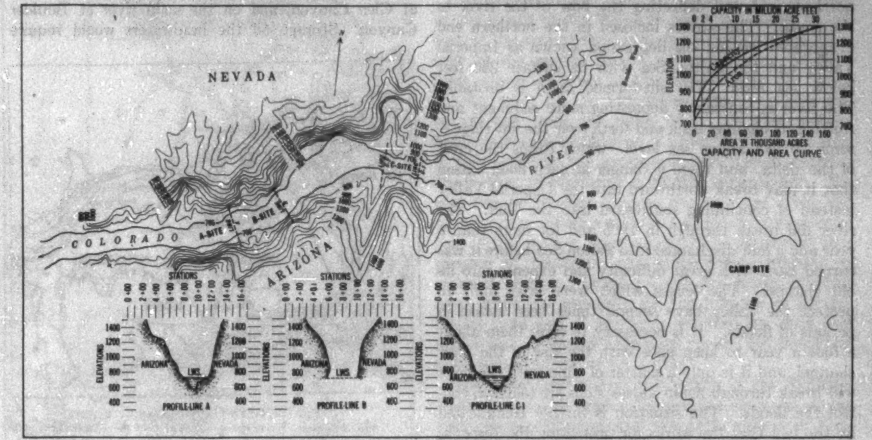

FIG. 3—BOULDER CANYON DAM SITES
Topography and Profiles.

The proposed Boulder Canyon site (Fig. 3) has certain distinct advantages over all other sites if considered wholly from the standpoint of the flood control and irrigation requirements of the Imperial Valley. It is comparatively near to the irrigable lands, and operation difficulties would be reduced to a minimum. It will intercept all floods on the river, except those from the Gila. It would even be possible to ameliorate flood conditions from the Gila by stopping all discharge from the main river while the Gila is in flood. If nothing but the flood control and irrigation requirements of the Imperial Valley were to be considered, there would appear to be no doubt of the superior advantages of the Boulder Canyon site. When, however, consideration is given to the problem of development of the river as whole, the situation is by no means so clear.

Both the Glen Canyon and the Boulder Canyon sites are likely eventually to be built, and both present engineering problems of magnitude. To provide the proposed minimum storage capacity of 21,000,000 acre-feet at Boulder Canyon and an equal amount at Glen Canyon will require dams of unprecedented height. Preliminary plans propose a masonry dam at Boulder Canyon some 530 feet in height above the river channel. When it is realized that the river channel has a depth of 135 feet below water level, that the river flows through a narrow canyon, and that floods in excess of 100,000 second-feet are likely to be encountered during construction, the magnitude of the engineering problems to be met will be appreciated.

Detailed investigation, particularly borings, have not yet been made of the Glen Canyon site, and the type of dam has therefore not been determined. If foundation conditions are not more unfavorable, this site should from the construction standpoint have certain distinct advantages over the Boulder Canyon site. The river forms a double loop at the dam site, one-half of which is 28,000 feet around but at its narrowest parts only 3600 feet across at water level, and only 2000 feet at 500 feet above water level. This condition provides better opportunity for handling water during construction than at Boulder Canyon and also affords better opportunity for constructing outlet works and spillway independent of the dam by carrying the one through and the other over the narrow section which separates the two sides of the loop.

IRRIGATION PROBLEM

When we consider the relation of irrigation to power development we find that only about one acre in thirty in the Colorado basin is irrigable, but that it has power resources more than sufficient to meet its needs for generations. Since it is likely to require all the agricultural products that its lands can supply long before it has put to use all its potential water powers, it would appear the part of wisdom to dedicate the waters of its streams to irrigation to the extent they can be efficiently used for such purpose, leaving water-power development to take the second place. If reasonably conservative practises are followed and all unnecessary waste avoided, there appears to be ample water in the Colorado and its tributaries to irrigate all lands within economic reach of the streams. The problem of water supply for such purposes is, therefore, one of equitable distribution; and this is the problem which the Colorado River Commission has been created to solve. I shall not discuss it further than to say that, if irrigation be assumed as the dominant use, there would still be opportunity to develop hundreds of thousands of horse power in the upper basin under properly developed plans and that, from the water which would be released from the upper section for the irrigation requirements of the lower section, there would still be available millions of horse power in the middle section.

Since there will be no irrigation development in the middle section of the river other than the probability of the provision of irrigation storage at the lower end of the section, and since no water will be withdrawn from the river in this section for such purpose, there will be no conflict between irrigation and power. In the upper section, however, such conflict is certain to exist. Not only will water be permanently withdrawn from the river, but storage reservoirs can not be fully used for both purposes. For this reason, as well as on account of the greater volume of water and the greater fall, the middle section is the most favorable for power development. But power development on the Colorado, as well as irrigation and flood control, requires seasonal storage. This is necessary not only to produce a regulated flow, but also, in the canyon section at least, to provide a protection against floods, for the narrowness of the river channel and the consequent restricted spillway length is likely to produce depths of discharge in flood season that might seriously restrict the height of dams that it would be save to construct.

On account of topographic conditions sufficient capacity for seasonal regulation can not be secured in the middle section except at Boulder Canyon, and that of course is available only for use at that site or below. For the greater part of the section storage must be either at the head of the section or in the upper river. If it proves feasible of construction, Glen Canyon reservoir is peculiarly well adapted for the purpose. It is situated at the crest of the steep canyon slope and appears to have a capacity sufficient to equate the flow of the river over a series of years.

The fact that this reservoir must eventually be built in connection with power developments below and that when built it is likely of itself to solve the flood problem of the main river has naturally raised the question, why build both Glen Canyon and Boulder Canyon, or if both, why build the latter first. The construction of Glen Canyon reservoir by eliminating flood conditions would make the construction of all dams in the river below far easier, cheaper, and safer. Nothing which may be done at Boulder Canyon will obviate in any degree the eventual necessity for Glen Canyon reservoir or reduce the difficulties of other construction in the canyon above. On the other hand, if Glen Canyon is built, the greater part of Boulder Canyon storage—as storage—would become useless. It would seem, therefore, that the prior construction of this dam could be justified only on one or both of two grounds. Either that the imminence of the peril to the Imperial Valley justifies the cost of the Boulder Canyon dam even if only temporarily required for flood control purposes; or that the cost is justified, independently of storage, by the additional power that could thus be produced by a dam of the height proposed. In any event, some storage below the Virgin is desirable, if not necessary, even if Glen Canyon reservoir is constructed, in order to regulate the water at that point to meet immediate irrigation requirements farther down the river. Which reservoir should be built first and whether the full capacity of both is needed are questions about which there is considerable difference of opinion. I shall only say that there appears to be enough doubt to warrant a thorough study of the upper site before commitment is made to Boulder Canyon, and that in such study due consideration should be given to power developments in the middle section as well as to irrigation and flood control on the lower section. I have placed emphasis upon this question of the location of primary storage, whether at the head or at the foot of the middle section, because it is a factor of great importance in the problems of power development and may determine the entire course of such development upon the river.

POWER DEVELOPMENT POSSIBILITIES

The extent of the interest in the power possibilities of the Colorado River (see Figs. 4 and 5) may be judged from the fact that there are on file with the Federal Power Commission 20 applications affecting the Colorado River and its tributaries aggregating four and one-half million primary horse power and six million horse power of estimated installation. It is, however, quite apparent that no such amount of power will be developed in the near future simply because it could not be disposed of. The rate of power development on the Colorado is a question of markets. The sites at the headwaters will gradually be developed to supplement the existing Utah and Colorado power systems. When we turn to the middle or canyon section, however, we find that local demands for power in this part of the Colorado basin are hardly sufficient to justify at the present time any large-scale development. The mining market of central Arizona probably would justify an initial development of some 100,000 horse power, but to justify large-scale development utilizing any such storage as proposed at either Boulder Canyon or Glen Canyon would require that primary markets be sought outside the basin, a situation involving long-distance high-tension transmission.

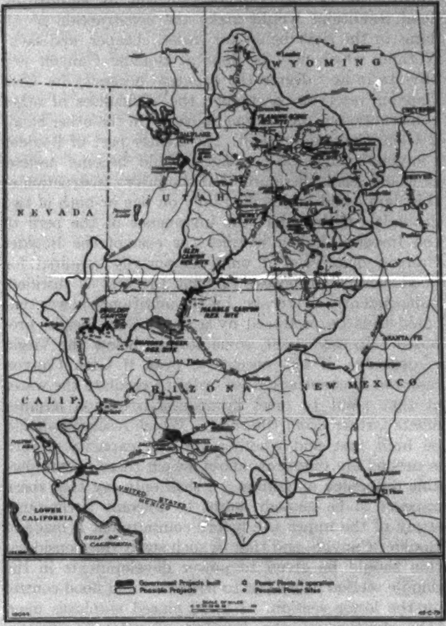

FIG. 4—COLORADO RIVER BASIN SHOWING POSSIBLE DEVELOPMENTS

Location of projects on file with the Federal Power Commission:

1.	Flaming Gorge Dam Site, Utah Power & Light Co.,	No. 165
2.	Swallow Canyon Dam Site, " " " " "	" 279
3.	Juniper Mt. Dam Site, " " " " "	" "
4.	Mabell Dam Site, " " " " "	" "
5.	Lily Park Dam Site, " " " " "	" "
6.	Blue Canyon Dam Site, " " " " "	" "
7.	Echo Park Dam Site, " " " " "	" "
8.	Island Park Dam Site, " " " " "	" "
9.	Split Mt. Dam Site, " " " " "	" "
10.	Minnie Maud Dam Site, " " " " "	" "
11.	Rock Cr. Dam Site, " " " " "	" "
12.	Rattle Snake Dam Site, " " " " "	" 158
13.	Kremmling Reservoir Site, Barker, W. J.	" 263
14.	Stillwater Canyon Dam Site, Green River Power Co.,	" 202
15.	Glen Canyon Dam Site, Southern Cal. Edison Co.,	" 111
16.	Marble Canyon Dam Site, Southern Cal. Edison Co.,	" "
17.	Diamond Cr. Dam Site, Girand, J. B.,	" 121
18.	Grand Wash Dam Site, Southern Cal. Edison Co.,	" 111
19.	Upper Boulder Canyon Dam Site, Los Angeles, City of,	" 238
20.	Old Callville Dam Site, Southern Cal. Edison Co.,	" 258
21.	Black Canyon Dam Site, Reclamation Site	
22.	Bulls Head Rock Dam Site, Southern Cal. Edison Co.,	" 258
23.	Parker Dam Site, Beckman & Linden Engineering Corp.,	" 30

The only section which at present seems capable of furnishing the requisite demand, and the section which gives greatest promise of increasing its demand in the near future, is the southern half of the State of California. Notwithstanding the great power resources of that state, objection is already being raised against the diversion southward of the electric energy generated from the waters of the central and northern sections of the state. With the continued depletion of its oil reserves and with increasing industrial and agricultural development, the time appears not far distant when California, should it maintain its present growth of power demand, would be required to go outside its boundaries for new sources of power, even if economic considerations did not lead it to do so at a much earlier date.

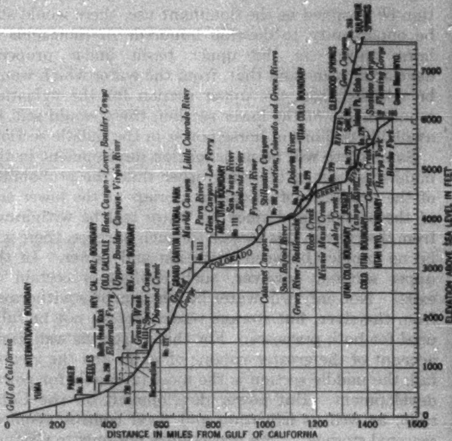

FIG. 5—PROFILE OF COLORADO AND GREEN RIVERS

Showing location of projects on file with the Federal Power Commission.
Nos. 158, 165 and 279, Utah Power and Light Company
No. 202, Green River Power Company
No. 263, W. J. Barker
Nos. 111 and 258, Southern California Edison Company
No. 121, J. B. Girand
No. 238, City of Los Angeles
No. 30, Beckman & Linden Engineering Corporation

The development of power in the basin of the Colorado for use outside will, however, be an advantage, not a disadvantage, to the people and the industries within the basin. The potential power available is more than the basin itself is ever likely to require. If power is developed on such a scale and at such a cost that it can be economically delivered in large quantities, hundreds of miles from the point of generation, it can be economically delivered near at hand in smaller quantities, and this fact, if the power is developed under proper auspices, would result in the extension of facilities to existing local markets and in the development of new ones; for the most complete disposition of its products is the ultimate object of power development. The mining areas within the basin, the railroads which traverse it, the towns within it and along its margin, all would be sought out as users of power once development were made and the main transmission system established. Distribution of power throughout a sparsely settled area is, however, likely to be attempted only through extensions from a transmission network constructed primarily to serve other and more extensive markets elsewhere. The states within the Colorado basin would never have secured the railroad service they now possess had they not been on the main routes between the Mississippi Valley and the Pacific Coast. They will be in a similarly favorable position with respect to electric power service when trunk transmission lines are constructed across their territories.

The final factor which determines whether power sites can be utilized, the degree to which they may be developed, and the distance to which the power may be transmitted, is of course, the unit cost of energy delivered. To a considerable degree unit costs are less as quantities increase. Particularly on a stream like the Colorado where, irrespective of the size of the project, large preliminary expenses will be involved and long and expensive transmission lines will be required, large-scale development is likely to prove much cheaper in construction costs per unit of available output than small-scale development. The extent, therefore, to which the water powers of the Colorado are to be developed and the degree to which they will be made to serve the interests of the Colorado basin itself are likely to depend largely, if not primarily, upon whether the power is developed in isolated independent units or in a system of interconnected plants with a transmission network extending over the entire territory. If development proceeds by independent units, a few restricted areas will get the benefit of such part of the resources as are developed. If the other plan is followed the entire basin and all the adjacent territory may share in the benefits. Such a plan, however, can be carried out only by agencies whose authority is not circumscribed by state lines—agencies in whose own interest it will be to extend as widely as possible the territory which they serve. Such a plan does not necessarily imply either a single ownership, or Government ownership; but it does imply such an interrelationship, at least, as will insure the operation in one interconnected system of the power developments on the Colorado River.

POLITICAL AND ECONOMIC CONSIDERATIONS

We come now to a brief consideration of what we have called the political relations of the problem. Under the provisions of The Federal Water Power Act, applicants for license must present evidence of having secured from the state, necessary rights for the diversion and use of water. It is the general rule of law within the Colorado basin that he who first puts the waters of a stream to use has a first right in their use. On this doctrine of priority of appropriation, extensive rights to the use of the waters of the Colorado have been acquired on the lower river, for it is that section of the river which is being the most rapidly developed. The fear has consequently arisen in the states in the upper section that, before the time when they can put what they believe is their share of the water to use, rights to such share will have been acquired on the lower river, particularly if power developments utilizing the full flow of the stream should be authorized on the middle or lower river. Because of this fear and in the hope that the matter might be settled without the endless interstate litigation that would otherwise be almost inevitable, a proposal was made that the several states affected enter into a treaty or compact by which they should mutually agree on the apportionment among themselves of the waters of the river. Under the provisions of the Constitution, such a compact or agreement between states requires the assent of Congress. This assent was given by Act of Congress of August 19, 1921, which authorized the creation of a commission to be composed of one representative from each of the seven interested states, who, together with a member appointed by the President, should form a Compact Commission, and should report their conclusions to Congress on or before January 1, 1923.

This Commission has been appointed with Secretary Hoover as the representative of the United States and chairman, has held several sessions, but has thus far come to no agreement. Under the terms of the Act creating the Commission, its authority is limited to the determination of an "equitable division and apportionment" of the waters of the river among the states. It has no authority to grant rights itself, and its powers do not conflict with those of the Federal Power Commission or other federal or state agencies. Since, however, its conclusions might affect or be affected by the approval of applications by the Federal Power Commission, action upon such applications has been suspended awaiting the conclusions of the Colorado River Commission.

There are also international relations involved. The Colorado River forms the boundary between the southwestern tip of Arizona and the Mexican State of Lower California. Below the Arizona line it separates Lower California from Sonora. Some 190,000 acres of land in Mexico are now being irrigated from the river, and it is estimated that 630,000 additional acres are irrigable, a total of 320,000 acres or 40 per cent of the irrigable area tributary to the river below Boulder Canyon. Under such circumstances it is manifest that international comity, if for no other reason, requires that this situation be taken fully into consideration in any plans of Colorado River development. In its Preliminary Report on the Problems of Imperial Valley and Vicinity of January, 1921, the Reclamation Service recommended equitable participation by the Mexican Government in the cost of storage works, and arrangements with that Government for the construction and maintenance of flood protection works on Mexican soil. Such participation and arrangements could, of course, be brought about only by the concurrent action of the two Governments.

There is also the question of the degree to which the United States should itself take part in power or other developments along the river. It is argued, and with apparent justification, that the cost of flood and irrigation storage is greater than the irrigation interests alone can bear and that, therefore, the Government should itself construct the works and recoup itself by sale of power, some 600,000 horse power of which could be developed at Boulder Canyon. Whether this arrangement would or would not effect an equitable distribution of benefits among irrigators and power consumers, I am not prepared to say.

There are furthermore those who advocate development at Government expense of all the powers along the Colorado River, the distribution of such power by the Government at cost, and the prohibition of any development by private capital on the river. This is, of course merely an instance of the age-long contest, between advocates of public and of private ownership and operation. On account, however, of the probability that it may be found necessary that the Government participate in the development of the river at least to the extent of furnishing flood protection, general action is unlikely to be taken upon the applications before the Federal Power Commission until conclusions have been reached upon the extent, if any, to which the Government should thus participate.

Finally agreement among the several interested agencies should be reached on the general procedure and the general plan of development to be followed on the river, in order that whatever work is done or projects constructed may fit into a scheme for the fullest practicable utilization of the river for all uses to which its waters are adapted. There is an apparent existing need for additional power in certain sections within the basin. The several interested agencies should, therefore, reach their conclusions at the earliest practicable date so that the present order of suspension may be lifted.

SUMMARY

The primary elements of a general plan for river development appear to be as follows: (1) Storage at the headwaters for irrigation in the upper section and for such power development in this section as can be accomplished without undue interference with irrigation; (2) storage below the San Juan of sufficient capacity to control floods and to regulate the water available at that point for power use in the middle section; and (3) storage below the Virgin sufficient, at, least, for regulation to meet irrigation requirements of the lower river and for such additional flood protection as may be necessary or desirable. If this or some similar plans can be agreed upon, and an equitable apportionment of the waters effected, the details of the immediate application of the waters of the river to their respective uses in the individual sections will be greatly simplified, and work may be started on the series of developments upon which the economic progress of the whole Southwest primarily depends.

Discussion

J. B. Fisken: One thought occurred to me when I read the paper and that is that we now have connection over the Idaho-Montana line through to Seattle, Tacoma, and I don't know just how far south, with a break between Tacoma and Portland, and some breaks in Oregon; and I don't think it takes any very great imagination to visualize the time when our plants in Eastern Washington will run in synchronism with plants on the Colorado River. It will not in any sense be transmission from Eastern Washington to Southern California, but it will be simply an interchange of current, our plants furnishing the load as required on the northern end and meeting the western Washington plants, the Oregon plants and so forth.

It is extremely interesting, and as far as I can see, extremely complicated. The question of ownership, of the lines, private, state or Federal, I think, is involved in this, and I am afraid that it is going to take a long time until development will finally take place.

220-Kv. Transmission

Southern California Edison Company System, and Some 220-Kv. Researches

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***Review of the Subject:**—The rapid growth in the demand for electric power and the increasing distances to which transmission is desirable, have constantly forced the use of higher transmission voltages.*

The Southern California Edison Company, having two single-circuit tower lines 241 miles long from its Big Creek hydroelectric plants to near Los Angeles, had the alternative of either duplicating these lines or of raising the voltage upon them. The latter procedure was found to be vastly the more economical. Other things being equal, the amount of power that can be transmitted varying with the square of the voltage, and the existing voltage being 150 kv., a doubling of capacity will result by raising the voltage to 220 kv.

To avoid the difficulties inherent in changing over generating and substations built for the lower voltage, and in which adequate clearances would be very difficult to obtain, it was decided to use auto-transformers at each such station, transforming between 150 and 220 kv. Additional sectionalizing switching stations will be built in the line, making six in all, so that the rebuilding of the line may be done without crippling service, and insulator testing can be done at any convenient time. An extension of the line 30 miles in length will be built so that the completed 220-kv. system will be 270 miles long.

Preparatory to the final design, a considerable amount of investigation and research was carried on. The best form of insulation that would fit existing towers had to be determined, standard suspension insulators being preferred over new untried designs. Laboratory high-voltage tests of insulation at oscillator frequencies of 30,000 and 50,000 cycles and at continuous 60 cycles were undertaken in order to get as much information as possible, all such tests being made in dummy towers so as to duplicate actual conditions as nearly as possible.

The next step was to equip 27 miles of one Big Creek line with additional insulators and shield rings and carry out field tests. This section of line was energized to 280 kv. for one month, and to 241 kv. for about five months, extending through the greater part of the rainy season. Considerable care was taken to obtain reliable measurements of voltage, current and corona losses.

The results of the laboratory and field tests lead to the firm belief that nothing extraordinary will happen with 220-kv. transmission. The difference between operation at this voltage and existing voltages will be only of degree. There seems to be no pressing need of new designs of insulator so that as new designs are developed they may be given the acid test of time on unimportant lines where their failure will be of small moment.

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THE imminent increase of transmission voltage from the existing maximum of 165 kv. to 220 kv. has been forced by the extremely rapid increase in the demand for electric power, which on the one hand in certain cases, rendered the acquisition of rights of way and building of new lines difficult to effect within the allowable time and upon the other, has led to the transmission of such large quantities of power over long distances, that the higher voltage was required to realize the lowest total cost per kilowatt-hour delivered.

The Southern California Edison Company was confronted with the problem of doubling the transmission capacity from the Big Creek hydroelectric plants to the territory surrounding Los Angeles. The solution depended upon the conversion of the two existing 150-kv. tower lines to permit of operation at 220 kv., together with such terminal changes as would allow existing plants to feed into the lines, substations to take power from them, and future extensions to be made.

The general plan decided upon was as follows:

Big Creek No. 1 and No. 2 plants of 32,000 (48,000 ultimate) and 48,000-kw. capacity respectively will remain unaltered, delivering power at 150 kv. to two 52,500-kv-a. auto-transformer banks installed close to each plant. Each auto-transformer bank will have sufficient capacity to convert the whole output of its respective plant to 220 kv., so that there will be full capacity in reserve units.

Big Creek plant No. 8, of 22,500-kw. capacity, was designed and built for 220-kv. operation, but is now operating upon 160-kv. taps of 220-kv. transformers. Upon completion of the 220-kv. system the transformers will be connected for the higher voltage and the plant will feed directly into the 220-kv. lines.

Big Creek No. 3, now under construction, is designed for 220-kv. operation.

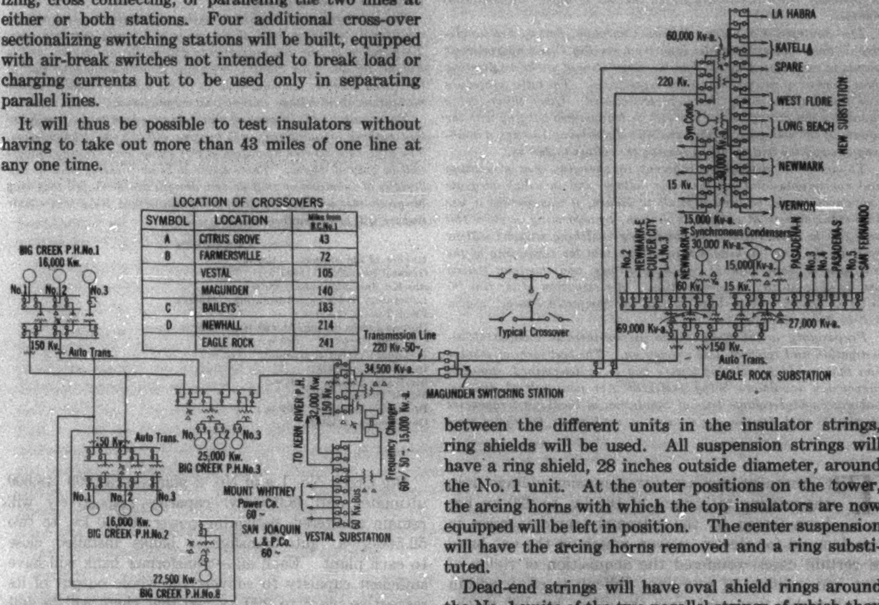
The Vestal substation, the first tap off the lines—109 miles from Big Creek No. 1—will be fed through two 52,500-kv-a. auto-transformer banks. The present terminal substation at Eagle Rock, 241 miles from Big Creek No. 1, will have two 110,100-kv-a. auto-transformer banks just outside the station. These substations will continue to operate as before, being fed at 150 kv. from the auto-transformers.

Presented at the Pacific Coast Convention of the A. I. E. E., Vancouver, B. C., August 8-11, 1922.

All auto-transformers will be star-connected, solidly grounded, with tertiary windings of kilovolt-ampere capacity equal to the transformer rating of the auto-transformer itself, and with a tertiary reactance of from 10 to 13 per cent.

At present the only switching station in the lines is at Magunden, 140 miles from Big Creek No. 1 and 101 miles from Eagle Rock. Oil switches of 220 kv. will be installed here, also at Vestal, permitting sectionalizing, cross connecting, or paralleling the two lines at either or both stations. Four additional cross-over sectionalizing switching stations will be built, equipped with air-break switches not intended to break load or charging currents but to be used only in separating parallel lines.

It will thus be possible to test insulators without having to take out more than 43 miles of one line at any one time.


BIG CREEK P.H.No.1
16,000 Kw.
No.1
No.2
No.3
150 Kv.
Auto Trans.
Transmission Line
220 Kv.-50~
34,500 Kv-a.
MAGUNDEN SWITCHING STATION
No.1
No.2
No.3
25,000 Kw.
BIG CREEK P.H.No.3
TO KERN RIVER P.H.
32,000 Kw.
150 Kv.
Frequency Changer
60~/50~, 15,000 Kv-a.
MOUNT WHITNEY
Power Co.
60~
SAN JOAQUIN
L.& P.Co.
60~
60 Kv.Bus
VESTAL SUBSTATION
50 Kv.
Auto Trans.
No.1
No.2
No.3
16,000 Kw.
BIG CREEK P.H.No.2
22,500 Kw.
BIG CREEK P.H.No.8
Typical Crossover
LA HABRA
60,000 Kv-a.
KATELLA
SPARE
220 Kv.
WEST FLORE
Syn.Cond.
LONG BEACH
30,000 Kv-a.
NEWMARK
15 Kv.
VERNON
NEW SUBSTATION
15,000 Kv-a.
Synchronous Condensers
30,000 Kv-a.
15,000 Kv-a.
No.2
NEWMARK-E
CULVER CITY
L.A.No.3
NEWMARK-W
PASADENA-N
No.3
No.4
PASADENA-S
No.5
SAN FERNANDO
60 Kv.
15 Kv.
69,000 Kv-a.
27,000 Kv-a.
150 Kv.
Auto Trans.
EAGLE ROCK SUBSTATION

LOCATION OF CROSSOVERS

SYMBOL	LOCATION	Miles from B.C.No.1
A	CITRUS GROVE	43
B	FARMERSVILLE	72
	VESTAL	105
	MAGUNDEN	140
C	BAILEYS	183
D	NEWHALL	214
	EAGLE ROCK	241

Fig. 1—Single Line Diagram—First Unit of 220-Kv. Transmission of Southern California Edison Company

This rather extreme amount of sectionalizing was considered advisable, as the number of insulators decided upon, viz. eleven to a suspension string, is about the minimum number that will afford satisfactory operation, and all the insulators on the lines will be meggered at least once a year and any accumulation of bad units forestalled.

Even had these considerations not prevailed, the sectionalizing was necessary for the reconstruction of the lines for 220 kv., as longer sections could not be taken out of service under the existing load conditions without undue drop in voltage.

It is planned to replace some of these air-break cross-over switches with oil switches in the future, with a view to automatic sectionalizing in cases of line trouble.

A 30-mile extension of the Big Creek lines will be built from Eagle Rock substation, or nearby, to a new substation which will lie east of Los Angeles and will deliver power to a rapidly developing industrial section of the city. Upon this line where no limitations of old construction exist, thirteen suspension units will be used.

In order to obtain better voltage distribution as between the different units in the insulator strings, ring shields will be used. All suspension strings will have a ring shield, 28 inches outside diameter, around the No. 1 unit. At the outer positions on the tower, the arcing horns with which the top insulators are now equipped will be left in position. The center suspension will have the arcing horns removed and a ring substituted.

Dead-end strings will have oval shield rings around the No. 1 units of the two parallel strings of which they are composed. At the tower end the existing arcing horn will remain.

Tie-down strings will have a shield ring around the top No. 1 unit, the numbering convention being to count always from the conductor towards the grounded end. The shields used at the bottom of suspension top of tie-down and line end of dead-end strings will be made of cast aluminum alloy. The rings for the top of center suspension strings will be of galvanized tire iron. All rings are so supported that they will retain their normal position relative to the axis of the insulator string whatever the inclination to the vertical of the latter may be. This material will all be manufactured locally.

For the purposes of voltage regulation all generating plants are equipped with Tirrell regulators, maintaining constant voltage at the generator.

At Eagle Rock substation will be one 30,000-kv-a.

and two 15,000-kv-a. synchronous condensers which are now in operation. The new 220-kv. substation east of Los Angeles will initially have one 30,000-kv-a. condenser and will be so designed that in the future, extensions can be made to accommodate three or more additional condensers, all condensers regulating for constant voltage by Tirrell regulators.

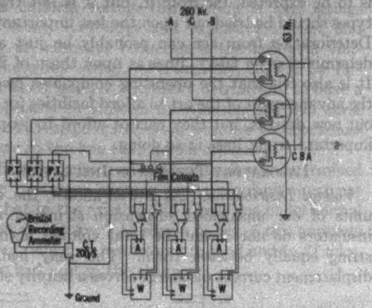


Fig. 2—Connections of Energizing Transformers and Meters Used on Field Tests

It is calculated that a total condenser capacity of 180,000 kv-a. will regulate for 240,000 kw. transmitted over two lines with zero regulation from generator to substation, the power factor of the load being taken at 0.85 lagging. While there are some theoretical considerations which render zero voltage regulation very attractive, it costs money, and there will be many cases where the marked increase in carrying capacity of the line, due to a slight drop in voltage from generator to substation, will be hard to overlook from an economical standpoint. This is a matter of distinguishing between feeder transmission lines and high-tension busbars and no general rules will apply.

Such calculations as have been made do not indicate the advisability of installing condensers at the middle point of the line, entirely satisfactory regulation and economy of transmission being effected by concentrating the condensers at the receiving end. It does not therefore seem necessary in this case to distribute condensers as has been done for several years past upon the Southern California Edison 60-kv. system, where, to describe one instance, in the transmission from Kern River No. 1 hydroelectric plant to Colton substation (a distance of 170 miles) synchronous condensers were installed at 110 and 143 miles from Kern River and at the end of the line, affording proper voltage regulation at intermediate points of the line and reducing line losses.

The 220-kv. oil switches will have a rupturing capacity of not less than 1,200,000 kv-a. Disconnecting switches for station use will be mounted upon separable post-type insulators. At Big Creek No. 8 these took the form of tripod posts, each leg composed of 14 standard 10-inch suspension disks connected by bolted flanges.

The general diagram of connections is shown in Fig. 1. This represents what may be called the first unit of 220-kv. transmission.

The existing clearance to ground upon the Big Creek lines is 25 ft. The reconstruction for 220-kv. entails the raising of a great percentage of the towers to afford a minimum clearance of 30 ft. to ground in all country susceptible of cultivation. In mountainous and the more inaccessible country, clearances will be established in accordance with rulings of the State Railroad Commission.

The towers will be raised bodily without interference with conductors or ground wire, and a structural steel, vertical sided extension frame bolted between them and their old foundation anchors, which will not be disturbed in any way. Among other advantages, the benefit of having old well settled foundations will be retained.

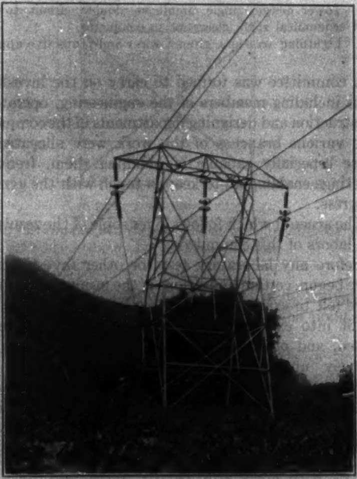


Fig. 3—Tie-Down Tower

The general appearance of the tower line with insulators equipped with shield rings is shown in Fig. 3 which illustrates a tie-down tower. A dead-end insulation is depicted in Fig. 4, both illustrations from the *Electrical World*. The rings that will be installed on the balance of the lines will differ from those illustrated in being only 2½ in. instead of 5 in. deep.

All this work is scheduled to be accomplished this year, so that actual operation at 220 kv. should be started quite early in 1923.

220-Kv. INVESTIGATIONS

When it was decided that investigations should be begun as to the best manner of making the change to 220 kv., a program was laid out which included:

1. The effect of shield rings, enlarged conductors, and other devices and expedients for improving voltage distribution over strings of suspension insulators.
2. The behavior of strings of various numbers of insulators under high-frequency, high-voltage oscillator discharges.
3. A duplication to a certain extent of the experiments made with the oscillator, and such other investigations as were desired, using 60-cycle high voltage.
4. Test under line conditions of the scheme of insulation which would be decided upon as a result of the laboratory experiments.
5. As extensive corona tests as were practicable, to determine definitely the sufficiency of the existing cables on the Big Creek lines.
6. To note such other matters of practical or academic interest as might arise or develop during the tests.
7. A complete study of line regulation, synchronous condenser capacities required, and the most economical size of conductor for new lines.
8. Tower design, single circuit vs. double circuit towers, most economical span, clearance to conductor.
9. Lightning arresters, ground wires and protective apparatus.

A committee was formed to carry on the investigations including members of the engineering, operating, construction and designing departments of the company. The various branches of the work were allocated to those especially capable of handling them, frequent meetings enabling all to keep in touch with the general progress.

The account which follows gives some of the results of the labors of this committee.

Before any laboratory tests or other investigations were begun, certain limitations of the insulation problem were felt to exist. Firstly, the selected insulation had to fit into existing towers which could of course be raised, and otherwise modified, but which it was extremely undesirable to weaken mechanically; this latter restriction practically preventing any increase of clearance between conductor and tower being obtained by modification of the tower structure. Secondly, it was felt that every effort should be made to utilize standard suspension insulators.

The modern 10-inch suspension insulator has reached a high perfection and can be bought of several manufacturers. Several years were required to bring this insulator up to its present excellence and to prove it. The insulator is an innocent looking little thing, but it is doubtful if the manufacturer, and still less the user, can always forsee the troubles that may arise from making even apparently minor changes in its shape. At all events the user cannot be sure that a new type will be satisfactory for his purpose until it has been tried out for several years. It therefore appeared logical and to be better business to use the standard insulator whose behavior and endurance are fairly well-known, predicated always upon satisfactory insulation being obtainable rather than to experiment with something new.

This point of view is not to be taken as indicating that no further advance in the art of insulator design is to be expected, far from it, but it is felt that new types should be tried out upon the less important lines. Deterioration from age can probably be just as well determined upon 60-kv. lines as upon those of 220-kv. It is also felt that the operating companies owe it to the advancement of the art to afford facilities for trying out new designs, but they cannot afford to jeopardize important trunk lines in so doing.

LABORATORY TESTS UPON INSULATION

Voltage Distribution. As is well-known, the several units of our unshielded suspension string of similar insulators do not divide the total voltage across the string equally between them. This may lead to a displacement current discharge across a heavily stressed unit if the surface condition of the porcelain is poor from dirt and moisture; such a partial failure of the string may set up oscillations followed by a string flash-over. Whether any such action actually occurs in practise is open to question. Efforts to render the surface of a string of insulators conducting with salt solution have only given negative results in the sense that before a non-unit string, normally used at 87 kv. to ground, could be made to flash over at as low a voltage as double line potential, an amount of conducting material had to be deposited upon its surface that was many times that found upon insulators in ordinary service.

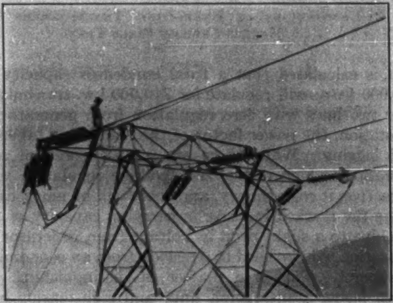
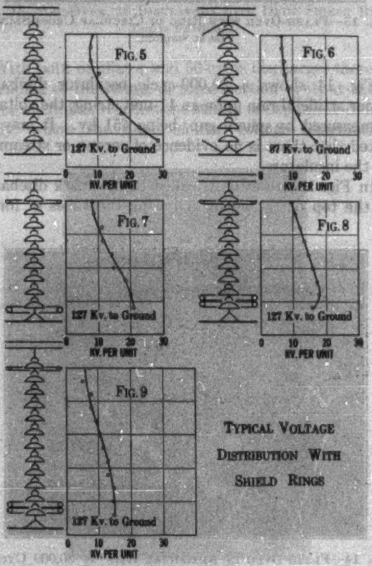


FIG. 4—ERECTING SHIELD RINGS ON DEAD-END TOWER

It seems advisable however to equalize this voltage to a certain degree as between units in a string. Through the kindness of Prof. Harris J. Ryan, a series of tests with the high-voltage potentiometer was made at Stanford in 1920 and 1921 to determine the quantitative effect of shields of various proportions. Typical distribution curves are shown in Figs. 5, 6, 7, 8 and 9. Practically any desired distribution can be obtained, even with strings composed of insulators all of the same kind, and further variation and complication is obtainable by mixing units of different internal capacities.

With all similar units in the string it is difficult to obtain a uniform voltage distribution in long strings without using very large and expensive shields, and suffering an excessive reduction in the flash-over voltage of the whole string. Fortunately, as will be further discussed later, it is actually detrimental to have a close approach to uniform distribution and still worse to have an inverted distribution with less voltage across units near to the line than across others.

As a firm basis from which to start it was determined that the maximum voltage across any unit must not exceed that in the existing Big Creek line under normal operation at 150 kv. As shown in Fig. 6 this amounts to 16.8 kv. when all insulators are good and to 21.5 kv. with one bad unit in the string.



Figs. 5 to 9—Voltage Distribution With and Without Shield Rings

Tests at Stanford.

The design of ring finally adopted (See Fig. 10) gives a maximum of 17.0 kv. when all insulators are good and 20.8 kv. under the worse condition for one bad unit.

It was found that extension downward of the outer lip of the inverted U-shaped ring, making the ring twice its original depth, had no measurable effect upon the voltage distribution. Similar deepening of the inner lip had, however, a noticeable effect in reducing still further the voltage across the No. 1 unit.

The additional cost of deepening the ring in this way was considerable which the small effect produced did not justify.

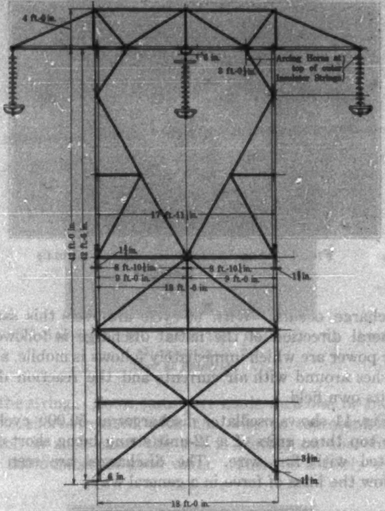


Fig. 10—Standard Big Creek Tower with Insulation and Shield Rings as Finally Adopted

Arc-over. The most instructive test of an insulator is its behavior under high voltage up to the point of arc-over or flash-over.

Overstress of particular units and parts of units becomes apparent in the dark by the formation of corona, and the path taken by the discharge when flash-over occurs gives a valuable indication of the likelihood or otherwise of damage being done to porcelain by arc-overs on the line.

A great number of studies was made with Prof. Ryan with oscillator discharges at about 50,000 cycles, with Mr. A. O. Austin at 30,000 cycles, and with Mr. F. W. Peek, Jr. at 60 cycles. It was thus hoped to obtain information upon the behavior of high-frequency effects, which may or may not actually occur in the line, and also to determine the factor of safety to normal-frequency voltages.

These tests were all made with insulators suspended in dummy towers so that the flux distribution might be approximately the same as it would be on the line.

This precaution is necessary, and it may here be emphasized that flash-over tests made under different conditions as to grounded insulator supports and energized conductors are not comparable for the same insulator arrangements.

The path of the discharge with oscillator frequencies and blue snappy flash discharges follows quite approximately the lines of flux distribution existing just before discharge occurs. With 60-cycle arc-overs this same general direction of the initial discharge is followed, the power arc which immediately follows is mobile, and flashes around with air currents and the reaction due to its own field.

Fig. 11—Flash-over at 50,000 Cycles
Test at Stanford.

Fig. 11 shows oscillator discharges at 50,000 cycles, the top three units of a 12-unit string being short-circuited with fine wire. The discharges are seen to follow the lines of force in a general way.

Fig 12—Flash-Over with Inverted U-Shaped Ring
Test at Stanford.

Figs. 12 and 13 show arrangements identical except as to the cross-sectional shape of the shield ring. In Fig. 12 the ring has a ∩ section, and in Fig. 13 the ring is made of round pipe. It will be noticed that the discharges start from the outer lower edge of the ring in Fig. 12 and are directed further outward from the insulator string than in Fig. 13, where one discharge cascaded the top three units. These illustrations represent 30 closings of the switch in the oscillator circuit. At each closing, lasting perhaps one second, the discharge would usually take place along only one of the flashes shown, although occasionally a flash-over would split between two or three directions.

Fig. 13—Flash-Over with Ring of Circular Cross-Section
Test at Stanford.

Fig. 14 shows a 30,000-cycle oscillator discharge under artificial rain upon an 11-unit string, the voltage, as measured by sphere gap, being 451 kv. It may be noted that there is no evidence of corona or streamers on the insulators.

In Fig. 15 attention is called to the spark discharge to the top of the string following the tubes of force. The insulator string is so long, 13 units, that the majority of the discharges goes to the tower braces. The absence of corona on the insulators may again be noted.

Fig. 14—Flash-Over in Artificial Rain at 30,000 Cycles
Test at Barberton.

Figs. 16 and 17 illustrate the effect of the shield ring in directing the arc outward from the insulators in the case of flash-overs under rain. There is not any lowering of the flash-over value although the arcing distance is reduced four inches by the ring.

Fig. 18 shows a flash over a dead-end string equipped with shield ring and arcing horn such as will be used on the line.

FIG. 15—ARC-OVER, 13 INSULATORS WITH DEEP SHIELD RING
Test at Pittsfield.

With both oscillator and 60-cycle discharges there is cascading of the string, or some portion of it, at those parts where flux reenters the string, or expressed differently, where the slope of the voltage distribution curve changes sign as in Fig. 19. The oscillator seems to cause rather more cascading than does 60-cycle voltage.

FIG. 16—ARC-OVER IN ARTIFICIAL RAIN, WITH DEEP SHIELD RING
Test at Pittsfield.

In Figs. 20 and 21 is summarized a number of arc-over tests at 60 cycles with different numbers of units in the string. These tests were made with different kinds of shield rings placed at various heights above the conductor, thus giving different arc-over values for the same length of string. Points shown as full circles indicate tests where cascading occurred. Clear circles are for tests where the arc-over was clear of the string. Some tests were made with one or more units short-circuited with fine wire to represent bad units; in such cases the test is plotted on the chart for the number of good units. There is a fairly well defined line of demarkation between the regions of cascading and of clear arc-over, which is interpreted as indicating that, for the particular tower arrangement used, a certain length of string, or number of units, can be forced up to a certain maximum arc-over voltage without cascading, but that if, by lowering the shield

FIG. 17—ARC-OVER IN ARTIFICIAL RAIN—LOWER ARCING HORNS ONLY
Test At Pittsfield.

FIG. 18—ARC OVER DEAD-END STRING
Test at Pittsfield.

ring for instance, the flash-over voltage is increased, then cascading will occur. The two curves show the extent to which the clear arc-over voltage is affected by the tower structure surrounding the center conductor, as compared with the outer conductor.

Fig. 19—Flash-Over at 50,000 Cycles Showing Cascading in Relation to Voltage Distribution
Test at Stanford.

The relation between the arcing distance, measured in a straight line and not along the path of the discharge, and voltage is shown in Fig. 22 with, for comparison, the ordinary spark gap curve for points.

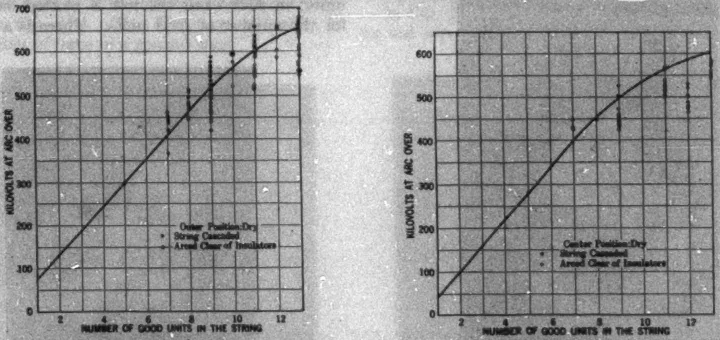


Fig. 20

Fig. 21

Fig. 20 and 21—Summary of Arc-Over Tests at 60 Cycles of Suspension Strings with and without Shields
Characteristic cascading curves—Locke No. 5996 insulator in Big Creek tower.
Tests at Pittsfield.

Arc-over under rain conditions will start as a cascade but by a proper proportioning of the shield ring the first three or four units can be prevented from cascading, the initial discharge taking place from the ring to the cap of No. 3 or No. 4 unit and then cascading the rest of the string. With sufficient power behind the arc, it will almost instantly leave the insulator string and flare out away from it, at all events in those cases where a gradual diminution in unit voltage duty obtains along the string. No quantitative evidence has been obtained as to how great a part is borne by the outward flux from the string in forcing out the arc from a wet string, but the tendency is in the right direction and should be taken advantage of. Such arcs over wet strings are shown in Figs. 16 and 17; the initial discharge is plainly marked, the whole mass of flame not existing all at one time but being a superimposed record of the wanderings of the arc.

To settle the question as to whether dirt or moderate roughness of the surface of the ring would materially affect the flash-over value the experiment was tried of attaching a pointed piece of wire one-half inch long to the ring, the wire sticking out normal to the ring surface. No difference in flash-over value could be detected whether the point was in position or not. It was concluded that the ordinary roughness of commercially manufactured articles would be immaterial.

It has appeared from these studies that in order to prevent damage to a string of insulators subjected to accidental flash-over, the following points of design should be adhered to:

1. The voltage gradient along the string from conductor to grounded support should gradually decrease.

2. A shield ring should surround the No. 1 unit so proportioned that even under rain conditions discharge will start from it rather than from the hardware of the first unit. The ring should be complete so as to permit an arc to travel round it without crossing into the string.

3. The cross-sectional shape of the ring should be such that an arc-over produced by sufficiently high voltage will start from a part of the ring where the field of force, or flux, is strongly divergent from the insulator string, thus forcing the arc well out and away from the insulators. The point of origin of the arc-over

is controlled by the radius of curvature of the cross-section of the ring in its various parts.

4. A top shield ring is advisable both to prevent an increase in voltage gradient over the upper third of the string and also to allow of the arc traveling around clear of the porcelain.

FIELD TESTS

After the conclusion of the laboratory tests a portion of the West Big Creek line, 27 miles in length, was cut out of regular service, and equipped for high-voltage testing on a scale approximating more to actual service conditions than could be obtained in any laboratory. Some account of the results has appeared in the *Electrical World* of February 11th, 1922, with a corrected table of coefficients in the May 6th number.

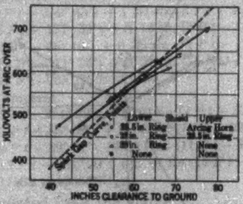


FIG. 22—RELATION BETWEEN CLEARANCE TO GROUND AND ARC-OVER VOLTAGE AT 60 CYCLES

For the sake of convenience and easier reference some of the substance of the article will be included here.

The purpose of the tests was to obtain:

1. Measurements of corona loss under such atmospheric conditions as might occur, and the determination therefrom of constants for weathered aluminum cables of large size.

2. A determination of the charging current of a line equipped with shielding devices and a comparison with calculated values.

3. A study of insulation.

4. Miscellaneous data.

The physical constants of the line are:

Conductors: Steel core aluminum, core 7-strand 78,500 cir. mils; aluminum strand 605,000 cir. mils; diameter 0.96 in.; horizontal construction, spacing 17 ft. 3 in.; average height above ground 33 ft.

Ground Wire: ½-in. steel 7-strand cable.

Towers: Structural steel.

Insulators: Cap and pin standard 10-in. suspension.

Transpositions: None.

At first two insulators were added only to those suspension strings where not less than normal clearance to ground would remain after so doing, this resulted in there being:

249 Suspension strings of 9 units.
42 Suspension strings of 11 units.
348 Dead-end strings of double 13 units.
48 Tie-down strings of one more unit than the corresponding suspension.

The shield ring was of a slightly different design from the one that will be used for the conversion of the complete lines but had practically the same electrical characteristics.

It had developed in laboratory tests that an arc-over in the central position of the tower would most frequently ignore the arcing horns at the top of the insulator string and go to the cap of the top unit . It was feared that this would endanger this unit and possibly some below it, so a lighter type of shield ring was installed around the top unit of all center position strings. In the outer positions the tower structure does not so effectively shield the arcing horns, and flash-overs go to them. No upper ring was put there and the arcing horns were left in position.

The lower end of all suspensions had shield rings, as had the line ends of dead-end strings, horns being left at the tower ends of these latter.

Tie-down strings had rings around their top units, the rings being similar to those used at the top of center suspensions.

The line was energized from three 4500-kv-a. 150,000/72,000-volt transformers, having various taps, connected in star on the high side with neutral grounded. For the first tests the low side was connected in star on the 36,000-volt tap and fed from the 64,000-volt (nominal) bus at Eagle Rock substation.

Corona Loss. Realizing that for the results to have any value, fairly accurate measurements of voltage and power would be necessary, some care was taken in the selection and calibration of instruments.

For the measurement of voltage, taps were brought out from the high-tension winding of each transformer near the grounded end and the ratio determined of the voltage from tap to ground compared with the voltage across the whole high-tension winding. This was found to be 7.1 kv. to 150 kv. The tap voltage was measured in service through 200-watt, 11,000/110-volt potential transformers whose only other load was the potential coils of Weston wattmeters.

The voltage between phases was found to be well balanced so that ordinarily the voltage from only one conductor to ground was read and recorded.

The load upon the energizing bank of transformers not exceeding 7 per cent in kilowatts of their rated capacity and being practically constant in kilovolt-amperes, voltage readings were taken off the low side of the transformers through potential transformers for many of the tests, the proper ratio being determined by comparison with readings on the voltage tap on the high side. The rise of voltage along the line was calculated not to exceed 0.3 kv. and was neglected.

Readings were taken regularly by the switchboard attendants to the nearest 0.5 volt on the meter, corresponding to 1.25 kv. on the line. This lack of precision was to some extent compensated for by the number of readings, a reading being taken every two hours except in rainy weather when hourly records were kept.

Power delivered to the line was measured by three Weston laboratory wattmeters calibrated, down to a power factor of 0.04 leading, against standards in the laboratory of the Southern California Edison Company, these standards having been previously checked by the Bureau of Standards. Checks were also made against oscillograph records as detailed later.

When tests were first planned it was hoped that the losses on each conductor would be determined separately; the effect of the different capacities between pairs of conductors due to the three conductors being in a horizontal plane and conductors and ground, there being no transpositions in the line, was overlooked. The effect of these capacities is illustrated in Fig. 23 where *A G*, *B G*, *C G* are the conductor voltages to ground and *A B*, *B C*, *C A*, *B A*, *B C*, *A C* are voltages, between conductors representing the relative times at which the first letter becomes a positive maximum to the second.

Assume first that there are no losses. Consider the conductor *A* one of the outer conductors; its charging current, considered as a condenser to ground is I_{AG}. There is also the condenser formed by conductors *A* and *B* and and *A* and *C* respectively, *C* being the center conductor. These have charging currents I_{AB} and I_{AC} the resultant line charging current being I_A. On account of the capacity *A C* exceeding that of *A B* the current I_A is displaced more than 90 degrees ahead of the voltage *A G*. The wattmeter fed by *A G* and I_A therefore reads backward when connected normally. For similar reasons wattmeter *B* reads forward and wattmeter *C* reads zero, with a circuit symmetrical about conductor *C* the sum of the wattmeter readings is zero.

The effect of losses in the circuits is to reduce the negative reading of wattmeter *A* finally rendering it positive in increasing degree as the loss increases. Both *B* and *C* wattmeters read positive with increase of losses, the sum of the three readings being the total power. Some considerable knowledge of the various circuit capacities is therefore required before the losses upon individual conductors can be determined. In the present case, including as it does three conductors and a ground wire on the one tower line and a similar adjacent line, the currents and voltages in the two lines having various phase displacements, and the capacities varying to some extent with the corona, the mathematical solution becomes complicated.

As a further check upon instrumental and systemic errors the instrument potential transformers were interchanged, wattmeters were interchanged, phase rotation upon the low side of the energizing transformers was changed, each of these changes being made singly at a time, no readable change in losses was effected by interchange of wattmeters or potential transformers.

The effect of changing rotation is given in Table I.

TABLE I
Effect of Phase Rotation upon Wattmeter Readings

Conductor Phase	West *C*	Center *B*	East *A*	Sum of wattmeters
Wattmeter reading	− 6.0	+ 0.5	+ 6.5	1.0
Phase	*A*	*B*	*C*	
Wattmeter reading	+ 6.0	0	− 6.0	0.0

The positive and negative readings interchange with the phase interchange in accordance with the vector diagram Fig. 23. The difference of 1.0 in the sum of the readings is equivalent to 0.33 kw. per mile of conductor; the readings were necessarily taken some hours apart.

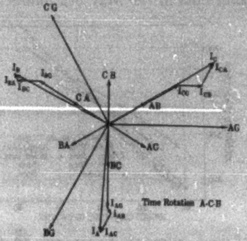


FIG. 23—VECTOR DIAGRAM OF CURRENTS AND VOLTAGES WHEN METERING CORONA LOSSES

The magnitude of the effect of induction from the parallel line was determined roughly by energizing the test line from a separate generator, at a slightly lower frequency than obtained on the paralleling lines. As the phase relation between the two lines changed, the wattmeter readings oscillated between minimum and maximum readings. The extent of the oscillation is given in Table II as follows:

TABLE II
Test for Induction from Parallel Line

Phase	*C* Wattmeter reading	Amperes	*B* Wattmeter reading	Amperes	*A* Wattmeter reading	Amperes	*A* Kv. to neutral
Min.	− 4.2	15.5	− 0.2	16.9	3.0	15.0	124.6
Max.	− 5.0	15.6	+ 0.2	17.2	6.0	15.8	124.6
Min.	− 5.2	17.1	− 0.4	18.8	4.2	16.8	137.3
Max.	− 5.9	17.2	+ 0.2	19.0	7.2	17.4	137.3

The larger swings of the *A* wattmeter are due to its being undamped. Both *C* and *B* wattmeters had well damped movements. The period of the swings was of the order of one or two per second. The maximum and minimum readings were not simultaneous in the three meters and it is felt that the effect of the parallel circuit upon the sum of the three readings was very small.

The practical requirement was to determine the total losses and this is given correctly by the sum of the three wattmeter readings.

The sensitiveness of the wattmeters was such that the sum of the three scale division readings multiplied by 26.4 gave the total loss in kilowatts; the routine readings were taken to the nearest half a scale division.

The relative readings of the three wattmeters is shown in Figs. 24 and 25, which indicate that the variations are according to the theory of the vector diagram Fig. 23.

As a still further check upon the wattmeters, though it was only a rough one, oscillograph records of voltage and current were taken simultaneously with wattmeter readings and the curves analyzed, by the eighteen-ordinate method, the results being as follows:

Phase A

Voltage in kv.:

$$200.3 \sin (P\,t - 359^\circ\, 43') + 1.31 \sin (3\,P\,t - 168^\circ\, 13') + 3.12 \sin (5\,P\,t - 177^\circ\, 59') + 0.16 \sin (7\,P\,t - 135^\circ\, 0\,0') + 0.27 \sin (9\,P\,t - 68^\circ\, 10') + 0.38 \sin (11\,P\,t - 123^\circ\, 40') + 0.16 \sin (13\,P\,t - 71^\circ\, 33') + 0.27 \sin (15\,P\,t - 101^\circ\, 19') + 0.11 \sin (17\,P\,t - 63^\circ\, 25')$$

Current in amperes:

$$24.82 \sin (P\,t - 274^\circ\, 29') + 0.19 \sin (3\,P\,t - 339^\circ\, 27') + 2.44 \sin (5\,P\,t - 86^\circ\, 59') + 0.38 \sin (7\,P\,t - 99^\circ\, 17') + 0.01 \sin (9\,P\,t - 89^\circ\, 57') + 0.14 \sin (11\,P\,t - 351^\circ\, 02') + 0.04 \sin (13\,P\,t - 231^\circ\, 20') + 0.04 \sin (15\,P\,t - 101^\circ\, 19') + 0.04 \sin (17\,P\,t - 189^\circ\, 28')$$

Power calculated from the above . . . . .206.3 kw.
Power measured 7.3 × 26.4 . . . . =192.7 kw.

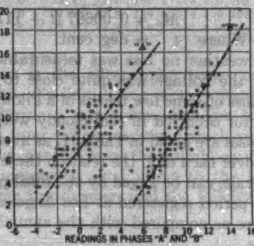


FIG. 24—RELATION OF THREE WATTMETER READINGS, 19.5-MILE TEST AT 161 KV. TO NEUTRAL

This is considered a satisfactory agreement when the difficulty of measuring oscillograph curves and the smallness of the wattmeter reading are taken into account.

$I^2 R$ losses in the transformer high-tension windings and line conductors were calculated.

From Peek's formula, after substituting the physical constants of the line; the logarithmic mean of the three conductor spacings being used:

$$P = \frac{0.01263}{\delta} (e - e_0)^2, \quad \text{also}$$

$$e_0 = 162.2\, \delta\, M_0 \quad ; \quad \text{whence}$$

$$M_0 = \frac{e - \sqrt{\dfrac{P\,\delta}{0.01263}}}{162.2\,\delta}$$

where M_0 = Surface irregularity factor and used here to include weather effects including storm
e = Voltage to neutral in kv.
P = Average kw. loss per mile per conductor
δ = Air density coefficient.

By the above formula each hourly and two-hourly observation was calculated and the corresponding value of M_0 found that would satisfy the quadratic equation of loss.

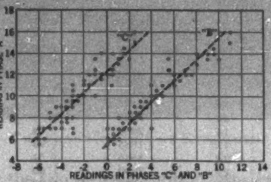


FIG. 25—RELATION OF THREE WATTMETER READINGS, 27-MILE TEST AT 141 KV. TO NEUTRAL

The line was energized at around 161 kv. to neutral from Sept. 16th, 1921, to Oct. 15th, 1921, when it was decided to lower the voltage to about 140 kv. to neutral. This was done for two reasons; the noise of the line at 161 kv. to neutral was annoying to property holders, and it was felt that data should be collected at a voltage nearer that at which commercial operation was going to be undertaken.

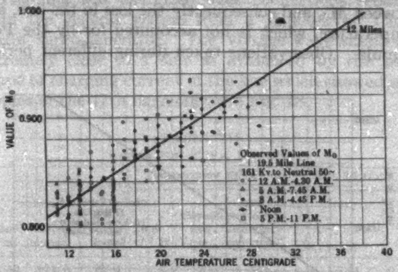


FIG. 26—VALUES OF IRREGULARITY FACTOR CALCULATED FROM OBSERVATIONS IN RAINLESS WEATHER

The selection of 140 kv. was made because its excess above the critical disruptive voltage on the test line was approximately the same as would exist with commercial 127 kv. to neutral at the points of highest altitude of the whole line. Data from the test line, at an average elevation of 1500 feet, would therefore correspond to commercial conditions at 220 kv. between conductors at between 4000 and 5000 feet. At 140 kv. to neutral the line was almost noiseless so that that voltage was suitable in all respects.

TABLE III
Daily Average Storm Losses at 141 kv. to Neutral

Date	No. of hours	Loss Kw-hr.	P Loss per conductor per mile	Temp. deg. cent.	Bar. cm.	$e - e_0$	Kv. to neutral e	Critical voltage e_0	Factor M_0
10/20	8	143	0.221	26	71.7	4.1	141.3	137.2	0.900
21	24	1191	0.612	19	71.7	6.8	140.0	133.2	0.853
22	24	1193	0.613	17	71.9	6.9	140.5	133.6	0.847
23	12	846	0.870	12	72.0	8.3	141.6	133.3	0.829
24	20	384	0.237	12	72.3	4.3	141.2	136.9	0.849
11/14	5	183	0.489	14	72.3	6.2	142.3	136.1	0.849
15	18	584	0.401	13	71.7	5.6	141.5	135.9	0.853
25	6	396	0.815	5	72.5	8.1	142.1	134.0	0.810
12/17	16	546	0.420	12	72.2	5.7	142.2	136.5	0.848
18	24	6452	3.34	10	71.7	16.2	143.3	127.1	0.789
19	24	11990	6.17	11	72.0	22.0	141.1	119.1	0.739
20	24	7285	3.75	13	72.1	17.1	139.5	122.4	0.764
21	24	2913	1.50	11	72.1	10.9	139.3	128.4	0.796
22	24	2827	1.45	7	71.7	10.7	140.1	129.4	0.796
25	24	3136	1.61	10	72.1	11.3	137.3	126.0	0.779
26	14	2127	1.87	12	72.1	12.1	138.1	126.0	0.783
27	15	2733	2.25	13	72.5	13.3	139.8	126.5	0.785
1/1	22	5303	2.98	14	71.8	15.2	139.0	123.8	0.778
2	14	2653	2.34	10	71.5	13.5	138.8	125.3	0.780
6	17	1683	1.22	6	72.3	9.9	143.6	133.7	0.810
29	24	4885	2.51	2	71.6	14.3	140.1	125.8	0.759
30	24	3690	1.90	5	71.5	12.3	142.2	129.9	0.795
31	12	1056	1.09	3	72.1	9.4	141.8	132.4	0.797
2/8	20	3980	2.46	10	72.2	14.0	142.6	128.6	0.792
9	22	2804	1.57	11	72.4	11.2	141.7	130.5	0.805
10	12	471	.48	11	72.5	6.2	140.2	134.0	0.826
11	24	3158	1.62	10	72.5	11.3	139.7	128.4	0.789
Total	497	74,612							
Average			1.853				140.8	128.9	

The results for the test upon 19½ miles of line at about 161 kv. to neutral are plotted in Fig. 26, including one observation upon 12 miles of line at a high temperature.

It will be noted that there is apparently a relation between M_0, and consequently the loss in the line, and temperature, which is not accounted for by the Peek formula. Observations taken during different periods of the day are distinguished in the chart with the object of determining whether variations of load in the adjacent power-carrying line were responsible for the variations in M_0 apparently however they are not.

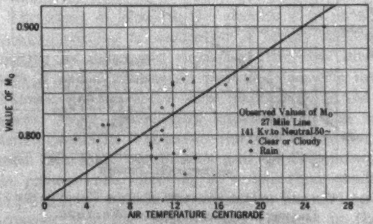


FIG. 27—VALUES OF IRREGULARITY FACTOR CALCULATED FROM OBSERVATIONS IN RAINY WEATHER

These observations were made during all kinds of weather with the exception of rain or snow, but include clear, cloudy, heavy fog, and misty conditions.

The value of M_0 does not seem to depend much upon such conditions but varies mainly with temperature, and for the particular conductor experimented upon is given by

$$M_0 = 0.00667\ (t + 111)$$

Where t = deg. cent.

In clear weather no loss was measurable at 140 kv. to neutral, the voltage was quite close to the critical point as a loss of some few tenths of a kilowatt per mile per conductor occurred in cool cloudy weather.

Storm losses are given in Table III as average quantities taken over each day, the relation these bear to the annual average can be gaged by the total precipitation during the period registered at Los Angeles which was 12.60 inches as compared with the annual average of 15.6 inches.

The plot of M_0 with temperature is in Fig. 27, the drawn line being the line of Fig. 26 produced.

The lowest values of M_0 observed occurred during the storms of Dec. 19, 1921 and Jan. 29, 1922. On Dec. 19th a total precipitation of 3.28 inches for the twenty-four hours was recorded at the Weather Bureau's station at San Fernando, close to the line, and not far from the middle of its length, and otherwise having climatic conditions averaging those along the length of the line.

Hourly readings for this day are given in Table IV and indicate the value of M_0 to be expected under heavy precipitation.

During the storm of January 29, 1922, a snow storm covered part of the line for a short time at noon, the precipitation recorded in Los Angeles for the hours 11 a. m. to noon being 0.52 inch. The losses and constants for the four hours of heaviest loss are given in Table V.

TABLE IV

Hourly Storm Losses Dec. 19, 1921 at 141 Kv. to Neutral

Time a. m.	Loss per conductor per mile P	Temp. deg. cent.	Bar. cm.	$e - e_0$	Kv. to neutral e	Critical voltage e_0	Factor M_0
12:05	5.77	10	71.7	21.3	141.6	120.3	0.747
1:05	2.84	10	71.7	14.9	142.6	127.7	0.793
2:05	3.65	10	71.7	16.9	141.6	124.7	0.775
3:10	4.31	10	71.7	18.4	141.6	123.2	0.765
4:03	7.08	10	71.6	23.6	141.6	118.0	0.734
5:10	7.23	10	71.7	23.8	140.5	116.7	0.725
6:05	6.92	10.5	71.8	23.3	140.5	117.2	0.731
7:10	8.05	10.5	71.8	25.1	139.5	114.4	0.714
8:20	6.26	10.5	71.9	22.1	140.5	118.4	0.737
9:00	7.89	11	71.9	24.9	141.6	116.7	0.725
10:15	9.03	11	71.9	26.6	141.6	115.0	0.715
11:07	9.36	11	71.9	27.1	141.6	114.5	0.712
12:05	8.05	11	71.9	25.1	142.6	117.5	0.731
1:15	7.72	11	71.9	24.6	142.6	118.0	0.733
3:00	4.47	11	72.0	18.8	141.6	122.8	0.762
4:10	3.81	11	72.1	17.3	139.4	122.1	0.756
7:10	2.35	11	72.1	13.6	139.4	125.8	0.780
8:10	4.85	11	72.2	19.5	141.6	122.1	0.756
9:10	3.65	11	72.2	12.3	143.7	131.4	0.813
10:20	7.31	11	72.2	24.0	139.4	115.4	0.715
11:10	3.65	11	72.2	17.0	139.4	122.4	0.758
12:20	4.31	11	72.2	18.4	137.3	118.9	0.736

TABLE V

Storm Loss Jan. 29, 1922

Time a. m.	P	Deg. cent.	Bar cm.	$e - e_0$	e	e_0	M_0	Weather
10:15	7.89	6	71.5	25.1	139.4	114.3	0.701	Rain
11:00	7.85	6	71.4	25.0	139.4	114.4	0.703	Rain
12:00	8.05	6	71.3	25.3	139.4	114.1	0.702	Snow
1:00	6.26	6	71.2	22.3	139.4	117.1	0.722	Rain

Of interest is the effect upon losses of suddenly energizing an idle line during stormy weather. This was done during a rain storm, the line having been dead for an hour. The readings, which were of only relative value, were taken on the switchboard indicating wattmeter measuring total input to the low side of the energizing transformers and the following readings obtained:

TABLE VI

Initial Loss on Energizing Line

Time after closing switch	Wattmeter reading kw.
0	1150
15 seconds	700
30 "	500
45 "	400
1 minute	350
2 "	300

Upon another occasion a reading as high as 2500 kw. was obtained on first energizing the line after it had been idle for an hour in a rain storm, it being remembered that transformer losses are included.

It is not known where the extreme loss occurs but most probably it is over insulator surfaces.

The rapid decrease of loss with time shows to what extent the line and insulators dry themselves under the influence of leakage current. The quickness of the drying—a 50 per cent reduction of loss in 30 seconds—would indicate that there is not much to fear from strange voltage distribution effects upon insulators due to ordinary rain storms, as the effect of leakage current is to remedy the trouble; furthermore, the effect of wet surfaces is to increase the capacity of the insulators and produce a more even voltage distribution between them. The wave shape of the impressed voltage upon the line for the two series of routine tests was approximately as follows:

Fig. 28—Charging Current of Experimental Line

Series at	161 kv.	140 kv.
Fundamental amplitude......	100.00	100.00
Third harmonic..............	0.66	0.65
Fifth "	3.62	1.56
Seventh "	0.99	0.08
9th to 17th "	Less than 0.4	Less than 0.2

In addition to the continuous routine tests at approximately constant voltages a test on variable voltage was run on Oct. 12, 1921.

The line was energized over connections separate from the general system from a 15,000-kv-a. Curtis steam turbo-generator. The voltage wave shape was extremely close to a sine as evidenced by the wave shape of charging current of the line which showed only ripples of the 17th harmonic, see Fig. 28.

TABLE VII

Corona Test of 19¼ Mile Line

			Temperature 11° C			Bar. 72.0 cm.		
Time a. m.	Kv. to neutral	Kw. total loss	Kw. $I^2 R$	Corona loss kw.	Loss per conductor per mile	$- e_0$	e_0	M_0
12:50	124.6	26.4	8.8	17.6	0.301	4.9	119.7	0.743
1:05	116.2	0	7.3	..	..	..	..	..
1:20	133.1	13.2	10.1	3.1	0.053	2.04	131.0	0.813
1:30	139.4	66.0	11.4	54.6	0.934	8.57	130.8	0.812
1:43	147.9	118.8	12.5	106.3	1.818	11.97	135.9	0.844
1:55	155.5	264.0	14.0	250.0	4.275	18.34	137.2	0.851
2:05	158.5	356.3	14.8	341.5	5.840	21.45	137.1	0.850

The results are given in Table VII. Visual corona in the span between towers was not in evidence at 139.4 kv. but was plainly noticeable at 147.9 kv. The visual corona point is somewhere between these two values.

The value of M_0 calculated from this test is higher than would be in accord with the data of Fig. 26 at a temperature of 11 deg. cent. This is to be expected from the better wave shape of voltage used in the test of Oct. 12th. Assuming 146 kv. to be the critical visual point, the value of M_v, the visual irregularity factor can be calculated from Peek's formula.

$$e_v = 21.1\, M_v\, \delta\, r \left(1 + \frac{0.301}{\sqrt{\delta\, r}}\right) \log_e s/r$$

whence for the constant of the line
$M_v = 0.713$

TABLE VIII
Single-Phase and Three-Phase Corona Test
Date Jan. 3, 1922

Time a. m.	Kv. to neutral	Loss kw.	Charging current amperes	Circuit arrangement
8:10	140.5	26.4	18.1	Average Three-phase
11:00	142.0	13.2	18.5	Single-phase with idle conductor insulated.
11:22	141.2	13.2	18.5	
11:40	141.6	2.6	18.4	Single-phase with idle conductor grounded.
12:10	139.5	5.2	18.35	
12:15	141.2	10.4	18.5	
5:00 p. m.	142.6	0	18.0	Three-phase

Different observers' ideas upon visual corona differ so that this value may be considered in good accord with Peek's value of 0.72 for local corona.

To substantiate the form of the formula, which makes the corona loss dependent upon the voltage to neutral and not upon voltage between conductors, two of the energizing transformers were reconnected, with low sides in parallel on the same phases and high sides in series, middle point grounded, single and three-phase losses could be then compared, there being the same voltage to neutral in each case, as follows in Table VIII:

TABLE IX
Corona Loss at 127 Kv. to Neutral
Fair Weather

Altitude ft.	Temp. deg. cent.	Bar. cm.	δ	M_o	e_o	$e - e_o$	P
0	25						
500	25	74.8	0.984	0.900	143.6	..	..
1000	25	73.3	0.964	0.900	140.7	..	..
2000	25	70.6	0.929	0.900	135.6	..	..
3000	25	67.9	0.893	0.900	130.4	..	..
4000	25	65.4	0.860	0.900	125.5	1.5	0.03305
4500	25	64.2	0.844	0.900	123.2	3.8	0.2160
5000	25	63.0	0.829	0.900	121.0	6.0	0.5485
				Heavy Storm			
500	10	74.0	1.025	0.710	118.1	8.9	0.976
1000	10	72.5	1.004	0.710	115.7	11.3	1.605
2000	10	70.0	0.970	0.710	111.7	15.3	3.048
3000	5	67.0	0.931	0.660	99.7	27.3	10.11
4000	0	65.0	0.934	0.650	98.4	28.6	14.92
5000	− 5	62.5	0.914	0.600	89.0	38.0	19.95
		Average taken over whole length of line					3.46
				Average Storm			
500	10	74.0	1.025	0.800	133.1	..	..
1000	10	72.5	1.004	0.800	130.4	..	..
2000	10	70.0	0.970	0.800	125.9	1.1	0.0156
3000	5	67.0	0.931	0.774	116.9	10.1	1.384
4000	0	65.0	0.934	0.740	112.1	14.9	3.002
5000	− 5	62.5	0.914	0.706	104.6	22.4	6.930

In both three-phase and single-phase tests the voltage to neutral was only slightly above the critical disruptive point with only negligible losses in consequence. Had the voltage between conductors been the determining factor the single-phase loss with 283 kv. would have greatly exceeded the three-phase loss at 245 kv.

CORONA LOSSES ON LINE AT 220 KV.

From the various data accumulated it has been possible to estimate what the average annual loss from corona will be upon the two complete lines. There being considerable variations in altitude above sea level, losses have been calculated for different elevations at average temperatures for fair weather, heavy storm and average storm. The values of M_0 assumed for different weathers and temperatures are believed to be conservative. The resulting loss P in kw. per conductor per mile are given in Table IX.

TABLE X
Annual Kw-hr. Corona Losses at 127 Kv. to Neutral

Altitude feet	Precipitation inches	Annual loss per conductor per mile Kw-hr.
2000	20	10
3000	25	1114
4000	30	2898
5000	35	7805

The kw-hr. loss per annum involves not only the magnitude of storm losses but the duration of the same.

For want of a better method it has been assumed that these losses will be directly proportional to the annual precipitation in any locality. This is based primarily upon the observed data on the test line where a total loss of approximately 74,600 kw-hr. occurred upon 81 miles of single conductor during an average precipitation upon the line of 15.47 inches, or at the rate of 4820 kw-hr. per inch. From Table III it is seen that this rate of loss corresponded to an average loss per conductor per mile of $P = 1.85$.

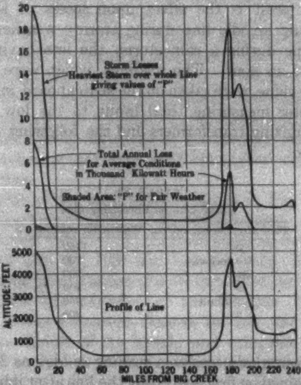


FIG. 29—PROFILE OF BIG CREEK LINE AND CORONA LOSSES

Expressing the annual kw-hr. loss per conductor per mile $= P_a$ then

$$P_a = \frac{74{,}600 \times P \times P}{81 \times 15.47 \times 1.85} = 32.2\, P \times p$$

P is the average storm loss at any altitude as given in Table IX. p = Annual precipitation in inches.

Applying appropriate precipitation data, Table X is obtained, giving annual kw-hr. losses at different altitudes.

Fig. 29 gives an approximate profile of the Big Creek lines together with the constants of Tables IX and X applied to it.

Fair weather losses occur only at 4000 ft. and above and are entirely negligible. The heaviest storm losses are plotted assuming the whole length of the line to be simultaneously involved which is practically impossible. However, under this extreme assumption the maximum loss, obtained by integrating the loss curve amounts only to 5000 kw. total for both lines; 2.08 per cent of their rated carrying capacity.

TABLE XI

Charging Current of Line Equipped with Shield Rings
Line Energized from System

Length of line miles	Voltage to neutral kv.	Changing current amperes			Avg.	Calculated	Measured in per cent of calculated
		A	*C*	*B*			
7	157.1	5.0	5.8	5.2	5.33	4.865	109.5
12	158.65	8.8	9.7	9.0	9.17	8.425	108.8
19.5	160.7	15.0	16.0	14.6	15.20	13.87	109.6
27	140.9	17.98	18.92	17.59	18.16	16.84	107.8
27	141.0	17.96	18.94	17.75	18.21	16.85	108.1

The annual loss shown by another curve in the same figure totals 780,000 kw-hr. At a 50 per cent load factor the load transmitted over the lines will be of the order 1,000,000,000 kw-hr. per annum. The average corona loss is therefore about 0.08 of 1 per cent and at higher load factors becomes correspondingly less.

Practically all of this loss will occur in a distance of 44 miles. Moderate enlargement of the conductor from a diameter of 0.96 in. to 1.05 in. and 1.10 in. according to elevation would eliminate this small loss.

CHARGING CURRENTS

The charging current of the line was measured by Weston ammeters having 25-ampere scales. The meters were connected directly in the grounded end of the transformer high-tension windings. They were correct to within less than 0.1 ampere.

The calculated current is based upon the logarithmic mean spacing of the conductors and exact hyperbolic formula, inductance being

$$L = 0.741 \log \frac{S}{r} + 0.304 \text{ millihenries per mile to neutral}$$

and capacity given by

$$C = \frac{0.0388}{\log \dfrac{S-r}{r}} \text{ microfarad per mile.}$$

In the 7- 12- and 19.5-mile tests *Y Y* connected transformers energized the line and the voltage wave shape is responsible for about 2 per cent increase in current, leaving on an average 7.3 per cent increase over the calculated. In the 27-mile test with delta-star transformers the wave shape was more nearly sinusoidal and but 0.8 per cent increase is due to harmonics leaving a final increase of 7.1 per cent. The average for the test upon a separate turbine with practically pure sine wave of voltage gives 7.6 per cent more than the calculated current.

FIG. 30—CHARGING CURRENT OF A SINGLE CONDUCTOR

It can therefore safely be said that the shield rings that will be used, together with the effect of other hardware, insulators, ground wire and adjacent parallel line, will cause an increase in charging current of about 7½ per cent above values calculated from the mean logarithmic spacing of the conductors by the above noted formulas.

TABLE XII

Charging Currents at 159.5 Kv. to Ground
19.5 miles of line

Phase	*A*	*C*	*B*
Three-Phase	14.80	15.50	15.10
Two Conductors	14.44	Out	13.6
	Out	14.20	14.30
	13.94	14.60	Out
One Conductor	13.78	Out	Out
	Out	14.40	Out
	Out	Out	14.08

A comparison of the charging current with either one, two or three conductors energized, the idle conductors being insulated from ground, is as follows, the voltage to neutral being the same in each case:

These values of charging current are not directly comparable with each other due to wave distortion when only one and two conductors are energized. They have a practical bearing upon what happens when switch contacts fail to operate simultaneously. Oscillogram Fig. 30 shows the distortion.

RESIDUAL CURRENT TO GROUND

The residual current to ground from the neutral connection of the transformers increases with the voltage. With delta connections such as will be provided by auto-transformer tertiaries the residual will be chiefly a fifth harmonic superimposed upon a fundamental of induction from the parallel second circuit.

The fundamental can be greatly reduced by having the proper phase relation between the two circuits, the best relation giving only approximately one-half the current, that will flow when the relative phase relations are most unsuitable.

Neither the test line nor the paralleling power line was transposed; transpositions will greatly reduce residuals and will be put in both lines before operating at 220 kv.

Peek has showed that grounding the line through transformer neutrals at several points along its length also reduces the residual. The Big Creek lines will be grounded at both ends and the middle, and no trouble from ground currents is expected to arise.

INSULATION

As the work of installing shields upon the line progressed additional sections were energized.

Sept. 16, 1921 7 miles of line were energized at 275 kv.
Sept. 27, 1921 12 " " " " " " 277 "
Sept. 30, 1921 19.5 " " " " " " 280 "
Oct. 20, 1921 27 " " " " " " 241 "

During the above time and up to Nov. 25th, 85.6 per cent of the suspension strings had 9 units, the remainder 11 units each, standard 10-in. suspension disks of cap and pin type being used throughout.

From Nov. 25, 1921 to Dec. 4, 1921 the line was out of service while additional insulators were installed, bringing all suspension strings up to eleven units each.

The line remained energized until Feb. 16, 1922 when the test had to be discontinued as the energizing transformers could no longer be spared for the purpose.

The first rain of the season came Sept 30, 1921, starting with gentle showers and mist and continuing thus intermittently throughout the day. At 8.52 p. m. the relays upon the 65-kv. side of the transformers cut the line out of service. The line was not put back into service until noon of the following day when it was switched onto the system at full voltage during the rain. No further trouble developed, but two or three days later, the cause of the trouble on the 30th was found by the patrolman to be a nine-unit suspension string which had arced over under about 161 kv. to ground. The arc-over was typical, having followed an identical path to that observed in laboratory flash-overs under artificial rain. It originated on the lower shield ring, then jumped to the cap of the No. 3 unit, then to No. 4, then jumped clear to No. 7 cap and cascaded both No. 8 and No. 9. The porcelain of the top No. 9 unit was cracked off on one side. This string with eight good remaining units went back into service in the rain and stood up until changed some days later. This was the only failure of insulation while the line was energized at 280 kv. It occurred under the most trying climatic conditions of the first rains, upon insulators covered with the accumulated dirt and dust of the whole preceding dry season.

During operation at 245 kv. the line kicked out on Nov. 6, 1921 and Jan. 18, 1922 without apparent reason in clear weather. The line was most carefully patrolled but no evidences of flash-over discovered. Later after the test was all over and the transformers were being put into normal service at 150 kv. one of them broke down and upon opening up the coils it was found that surface discharges across insulating barriers had taken place under the oil. There is no proof that this was the cause of the unexplained cutting out of the line but it seems probable.

FIGS. 31 AND 32—SUCCESSIVE STAGES OF ARC-OVERS ON LINE

With a view to observing the action of the insulation with its shields under arc-over, with more energy in the arc than was obtainable in the laboratory, intentional arc-overs were made by pulling a No. 40 copper wire across the insulator. Both still and motion pictures were taken of the arc which behaved entirely similarly to laboratory arcs with the exception that the light was vastly greater.

FIG. 33—CURRENT DURING ARC-OVER ON TOWER

For these flash-overs the line was fed from a 25,000-kv-a. steam turbine. The current in the arc was approximately 120 amperes. Fig. 31 shows progressive stages of an arc in the center position of the tower and Fig. 32 shows similar stages of an arc in the outer position. It is interesting to note the dying out of the arc in patches of incandescent vapor. These arcs lasted about 32 cycles, the relay then opening the circuit. No damage was done to porcelain or hardware. Fig. 33 gives the oscillogram of the performance; gradual decrease in the current is noticeable as the arc lengthens.

AIR-BREAK SWITCH

Some experimental work was done toward developing an inexpensive air-break switch for line sectionalizing. To settle the question as to whether such a switch would be able to break the charging current of a 27-mile length of line, one was set up in the line and opened. The arc held on for about six seconds, in quiet air, rising continually higher until it broke. The total length measured along the arc reached a maximum of from 60 to 70 ft. with a 23-ampere arc. Such an arc increases the charging current to the line due to wave distortion as shown in Fig. 34.

FIG. 34—CHARGING CURRENT OF LINE THROUGH LONG OPEN-AIR ARC

In view of the extremely long arc and the liability of its being blown into adjacent conductors it was decided to abandon the idea of breaking charging current upon air-break switches but to operate the sectionalizing switch stations so that the air-break switches would be used only for separating parallel lines.

TOWER DESIGN

Comparative studies were made of the cost of single- and double-circuit towers as follows: Clearances from insulator shield to tower of four five and six feet; conductors of 605,000, 1,000,000 and 1,500,000 circular mils of aluminum with steel core and copper conductors of resistance equivalent to the two larger sizes of aluminum; flexible and rigid towers, all towers to stand the unbalanced pull of any two conductors being broken and anchor towers to stand all conductors being broken on one side.

The combinations and permutations of these variables are many.

The final decision was for single-circuit towers, as costing no more per circuit than double-circuit construction.

Steel-core aluminum was preferred above copper, and the extra cost of obtaining six ft. clearance over that for four ft. was so insignificant that the minimum of six ft. was adopted.

The only condition under which double-circuit towers would seem advisable would be where it was extremely difficult to get rights of way. It also appeared somewhat hazardous to tie up such quantities of power as 240,000 kw. upon a single-tower line, at all events with the size of the whole system such as it will be for some few years to come.

PROTECTIVE DEVICES

The 150-kv. lightning arresters now in service at Big Creek generating plants, Vestal and Eagle Rock substations, will remain in operation, but it is not intended to install any arresters on the 220-kv. lines.

The two existing Big Creek tower lines have one ground wire on each and these will of course remain. They are of service in distributing ground current over several towers in the case of insulator arc-over. They are also felt to be of some slight mechanical advantage, although with rigid towers this would only be effective after a tower member buckled or a tower foundation washed out or gave way.

Mention has been made of the possibility of automatic sectionalizing of the line; this would be effected by balanced relays.

The method now used of breaking arc-overs is to lower the fields of generators and synchronous condensers until the arc breaks, and upon building up the field once more the generators pull into step, if they have fallen out of synchronism, and service is resumed in about one minute on an average.

Plans are under way to make this operation automatic which should result in a great saving of time.

CONCLUSIONS

Transmission at 220 kv. has been invested with a certain glamour, and the further investigation has been carried the more certain it appears that transmission at this voltage will only differ in degree from transmission at lower voltages, with which we are familiar. No new or startling effects are expected or appear probable.

The unequal voltage distribution over long insulator strings can be eliminated to the degree where individual units will be stressed less than they now are on lines in commercial operation. This is effected by shield rings which at the same time can be so designed as to keep any accidental arc well away from the insulators. Corona upon insulators and hardware is also prevented.

Standard suspension insulators can be used, so that 220-kv. transmission need not wait upon the design and trial of new types of insulator.

Transformers and switches are already developed, and have been built by more than one manufacturer.

The corona constants of large cables are known within rather narrow limits so that lines can be confidently designed to have definite known losses.

The charging current of commercial lines is also sufficiently well determined so that calculations of voltage regulation will be accurate.

There are therefore no apparent obstacles in the way of 220-kv. transmission, the only requirement being that the amount of power to be transmitted shall be sufficiently large, and the distance great enough to warrant the cost of 220-kv. equipment. The increased carrying capacity of the transmission lines then more than offsets the equipment cost and 220-kv. transmission becomes more economical than at any lower voltage.

Discussion

W. A. Hillebrand: Concerning the experiments on the disconnector switch, with regard to characteristic flash-over and the opening distance and clearance from the ground necessary to prevent the arc from shooting across the gap. Was any effort made to control the direction of flash-over by means of screens or guards which would reduce the gradient between the blade and the clip on the opposite side?

R. J. C. Wood: The only attachment to the switch is a vertical piece of pipe on the clip end which, when the switch was opened, formed, with the switch blade, a horn gap. This pipe was within three or four inches of the clip. The arc would very often hold onto this clip and pay no attention to the horn at all. There was no other attempt to influence the arc. The arc hung on for five or six seconds. We were satisfied that the arc was too long and that we had better not attempt to use such a switch for breaking charging currents.

W. A. Hillebrand: I think you misunderstood me, Mr. Wood, it is not in connection with the switch or breaking charge.

R. J. C. Wood: That was the charging current?

W. A. Hillebrand: Yes, but as I understood you to say, your disconnecting switches in the substation being 220, are mounted on the tripod that you had the nine-inch gap—linear gap necessary—a nine foot gap with regard to the striking distance to the ground, to prevent the possibility of an arc shooting across the open gap into the substation wire.

R. J. C. Wood: We had a big shield around the top of these posts, the circular disk to which the legs were attached was in the neighborhood of twenty inches in diameter, and formed a shield for the insulators distributing voltage in the same way that the shield on the transmission line does, it also prevented corona from the switch clip; but we did not try anything such as Mr. Hillebrand suggests. We were rather skeptical of any of these high-frequency effects existing at all. But we thought we had better make sure and arrange this side-gap so that if any of these unknown things did come in then we would be safe. In making the test we duplicated the set-up of the station, the walls, columns, etc., so that the field surrounding the switch would be the same in the test as it would be in the power house. Does that answer your question?

W. A. Hillebrand: Yes. One other thing which had better perhaps be discussed, that may be of extreme interest, and is of unquestioned importance, that is, the charging current of the line, the kv-a., its relation to the generator, the capacities available, the methods of energizing—of excitation, and finally of switch synchrouizing. That is, you have to energize the line with presumably a very considerable potential difference between the open end of your line and the system at Eagle Rock, which you will have to parallel.

R. J. C. Wood: First of all as to the charging kv-a. on the line, that will be 50,000 kv-a. for one line, the whole distance. After once getting started, there will be no difficulty, the line can be cut up into sections. If we have to, when we first start we can energize a section at a time adding generators as required. Also, we will have synchronous condensers at the load end. It is quite possible to put a condenser on the line and with a generator on the other end, bring the whole system up together from standstill, having the condenser on the end reduces the kv-a. required from the generator. One way of looking at it, part of the required 50,000 kv-a. comes out of the generator, part of it out of the synchronous condenser.

Apart from the magnitude, I do not see why operating problems are going to be any different from what they are now. With lines paralleled at the generating end only, one has a higher voltage than the other at the load end, when one is carrying the load, the other is not carrying the load.

Upon paralleling at the load end, loads and voltages in the two lines will equalize. There will be surges of course but so far we have been unable to record higher than an 80 per cent voltage rise when cutting in or out a 100-mile section of line and if the line is not good for that it is not good for anything.

With regard to determining what these high voltages—surges—on the line actually are going to be, all that can be obtained is an estimate based upon what we actually have now on the 150-kv-line; we have been working for some time to determine what voltage rise—surges—occur on that line in normal operation. We have had a lot of experience trying to make a surge recorder. We finally rigged up a device comprising substantially six points, which formed six air gaps of different lengths, varying from about the 64th of an inch to one eighth of an inch. These points are opposite a metal plate, and a kodak film moves along in the gaps. We have arranged to use an ordinary standard kodak film, load and unload it in daylight, the substation man or anybody else can handle it.

But we have had records on the surge recorder of as much as something less than 100 per cent rise of voltage. Of course there is nothing very precise about it. The first gap is set to discharge at slightly above the line voltage—possibly 10 per cent; the second gap at 25 per cent above voltage, the third at 50, the fourth at 100, and the fifth at 200 per cent above normal voltage. The highest surges that we have any record of so far, occur when we kill the bus in the station where we have this recorder installed. We have records of surges which occur when oil switches are opened at the far end of the line. The recorder, by the way, is on the bus at Eagle Rock substation, and we get records of switching operations at Big Creek, on the other extreme end of the line, but so far we have no records of anything like 200 or 300 per cent above normal voltage, which voltage would still be insufficient to flash-over an ordinary string of insulators.

We have been troubled with unexplained flash-overs on the Big Creek line. This has occurred at times when operation is apparently entirely normal. No switching is going on, fair weather, apparently no reason at all, the first thing we know there is a flash-over and the voltage is down and we are in trouble —which does not last very long, about from one to two minutes; but at the same time the larger the system becomes and the greater amount of power that is going over the line, the more serious, even what we call a momentary interruption, becomes. We are bending all energies now to try to determine what is actually going on in the present line, and we feel that until we get the answer to that we will not have the answer to the flash-over.

J. Mint, Jr.: Through the courtesy of Mr. Wood I had the opportunity of visiting and seeing the tests made on his system during the time they had on the high voltage, and I feel that there have been very few tests ever made—probably none ever made, of a line of such high voltage and that length on an actual transmission line. When the line was operating somewhere around 280,000 volts it was noisy and visible at night. The fact that the line was alive was easy to detect while it was operated with above voltage, but when the voltage was brought down to 220,000 volts you would have to be told that the lower voltage was on or you would not be aware of it.

There are one or two points in connection with Mr. Wood's paper where he tells you that the transmission line source is from star-grounded transformers and the receiving end connected to delta-delta transformers. He also tells you that they break these flash-overs by lowering the voltage. I believe that when we come to connect both ends of the transmission system star-grounded, that is the receiving end and the sending end, it will not be so easy to break the flash-over as it is under their present system where the receiving end is connected delta. I speak from our experience of 110,000-volt transmission lines where the receiving end is connected star-grounded as well as the sending end, and it is only in the case where we have one generator on the line and the energy is small that a flash-over can be broken, that is, the arc can be broken by lowering the voltage at the generator's end. The flashover arc is fed from both ends, whereas in Mr. Wood's system at the present time the real energy current in the flash-over arc to ground comes from the sending end.

We have found that the best method of getting rid of these flashovers, when they happen, (of course this can only be done when you have duplicate transmission lines operating in parallel) is by having one relay that is set very light for ground trouble, and three other relays set heavy so far as trouble between phases goes, you can have this line severed from the system at the receiving end and sending end in ample time before any damage is done.

Before we put in this system of residual relays which trip a line out with a moderately light ground, a flash-over to ground on our lines burned them down invariably. It was practically impossible, with hand operation for the operator to disconnect a line in time, before the wire had not been so severely damaged by burning that it subsequently pulled in two.

There is just one other point that comes to mind in regard to operating these lines at very high voltage and long mileage, and that is, if you have duplicate lines, and say one line is fully loaded and you want to switch in a second line, there will probably be a very large phase angle at the receiving end between the loaded and empty line voltage which will cause a severe disturbance of the voltage while equalizing the load by throwing them together. It has occurred to me that it might be possible in this case to close the line at the receiving end first and back voltage to the power house; then put on a separate generator and pull up some of the load and finally parallel the lines at the power house after the load was more equally divided over the two lines.

F. W. Peek, Jr., (by letter): Mr. Wood gives some very interesting and important data on the various factors affecting transmission at 220 kv. Mr. Wood's conclusions are not based on laboratory work alone but also upon the several years operating experience of the Southern California Edison Co. at a 30 per cent lower voltage. No radical changes in types of apparatus have been found necessary.

Standard ten-inch disk insulators will be used. The use of a simple metal ring shield will reduce the maximum unit stresses below those on present successful lines operating at lower voltages. The ring shield also serves as a very efficient arcing ring. Tests at 280 kv. on a thirty-mile section of line indicated that the line insulation will be quite satisfactory. There was only one arc-over. This occurred on a nine-unit string at 280 kv. during the first rains after the insulators had had a chance to accumulate dust for a full season. This is probably the worst condition to contend with in California. In connection with the arc-over of wet and dirty strings I wish to point out that unless the power supply is large, laboratory tests are of little value as an indication of arc-over voltages in practise. This follows because when the power is limited by the generator or transformer the heavy current flowing over the conducting surfaces lowers the voltage before an arc develops. The arc-over voltage thus appears much higher than would actually be the case on a large system.

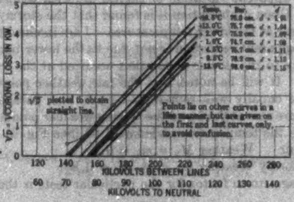


FIG. 1—CORONA LOSS MEASUREMENT AT VARIOUS TEMPERATURES

3/0 Seven Strand Cable. $r = 0.59$ cm. $S = 310$ cm. Single phase 60 cycles—1.09 km. Total Conductor Fair Weather.

The neutral of the system will be thoroughly grounded and thus eliminate dangerous oscillations and high voltages in case of an accidental ground on one or more lines. The permanent grounding of the neutral at the transformer also makes possible a much safer and better transformer. In fact, all creepage surfaces in the transformer are eliminated.

I am particularly interested in the corona measurements, because these measurements check so well with my own made on an outdoor experimental line in Schenectady in 1910 and discussed in the TRANSACTIONS.

It is interesting to make a comparison. In the Schenectady work it was also found that when a line had been idle and had become wet or dirty the loss was quite large on the first application of voltage. It was at first thought that this was due to leakage over the insulators. Tests were then made with a great many insulators bunched together so as to practically eliminate the line. It was found that the insulator loss was negligible under the above conditions and also in very heavy rain and snow storms. The excess loss was found to be due to the wet or dirty conductor surface. A study in the dark showed that water was sprayed from the conductor with a considerable increase in corona which extended out a great distance from the conductor surface. When there was fog, rain, snow or sleet this condition was found to be continuous.

In the formula for the disruptive critical voltage there is a factor, m_0, called the irregularity factor. This factor is used as a measure of the effect of roughness or irregularities of the conductor surface in lowering the critical voltage. It is unity for a smooth cylinder and less for cables. It is, therefore, not much affected by temperature and is constant for any weathered conductor. In fact, we found m_0 constant over a range of hot summer temperatures to below zero temperatures of winter, (See Fig. 1). Fog, rain and other conditions lower the critical voltage in the same way.

The weather factor, which may be called m_s, is variable. An average value of m_s for storms is 0.8. Mr. Wood has combined m_s and m_0 in one factor and denoted it by capital M_0.

Thus $M_0 = m_0 m_s$

I rather think it undesirable to do this because small m_0 is a constant which applies to a given weathered conductor anywhere, while m_s will vary with the location and the season. Mr. Wood shows an apparent variation of capital M_0 with temperature in Fig. 27. Upon examination it is found that the stormy weather points occur at the lower temperatures. I am inclined to believe that the apparent reduction is not due to the lower temperature but mostly to the storms or fog that occurred at the lower temperature. It will be noted that the fair weather points in Fig. 27 can be equally well represented by a line parallel to the temperature axis at 0.85 and the stormy weather points by a line parallel to the temperature ended at 0.80 (See Fig. 3).

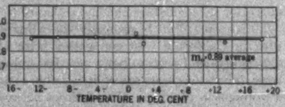


FIG. 2—3/0, 7-STRAND CABLE r = 0.59 CM. S = 310 CM. SINGLE PHASE—60 CYCLES—FAIR WEATHER

Then Fair Weather $M_0 = m_0 = 0.85$

Stormy Weather $M_0 = m_0 m_s = 0.80$

The average storm factor for the particular tests is therefore:

$$m_s = \frac{0.80}{0.85} = 0.94$$

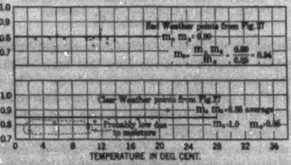


FIG. 3—BAD WEATHER AND CLEAR WEATHER POINTS DATA FROM FIG. 27

This factor on a long line would be the average of the various conditions along this line from dry weather to heavy storms. The apparent variation of capital M_0 with temperature would probably be quite different for different seasons in a given locality and for different localities. The variation of M_0 in Fig. 26 can be explained in the same way. It will be noted that the low points occur at the low temperature and are for the most part taken at night when fog is likely to occur. The variation of individual points at approximately the same temperature is also quite great at this time of day. For example, the variation of M_0 for 15 deg. to 17 deg. temperature for 12 A. M. to 4:30 A. M. is from 0.80 to 0.90. The shot gun effect of these diagrams should be expected for a long line where all of the variables are not under control or known. The starting voltages vary along the line and the meters record an average condition. Part of the individual variation is also due to the fact that the values were obtained at the lower or unstable part of the curve.

The above discussion is given as a possible explanation of the apparent variation of M_0 with temperature which Mr. Wood has found. It is not intended as a criticism of the value of the data. Such measurements on operating lines are of great value and the industry is greatly indebted to Mr. Wood.

Referring now to the m_0 factor as originally employed, it is desirable to obtain conductors in which this is as nearly unity as possible. It is necessary to give this factor greater consideration as the voltages are increased. A smooth cylinder would be a desirable conductor. Since in present practise cables are employed it is of great importance that the individual strands be regularly placed and free from burrs and points and other irregularities of manufacture. The loss near the critical voltage on a new cable will often be higher than on a cable that has "weathered" under the action of voltage when there is a tendency for the burrs to disappear by oxidation at the over-stressed points. In making measurements on new cables of different stranding we have found high losses near the critical voltage where strands had been mutilated in manufacture.

It may be of interest to point out further possible irregularities in manufacture that will affect M_0. The Southern California Edison conductor which is highly satisfactory for 220 kv. is made up of individual strands about one-tenth of an inch in diameter. A single strand would have corona at very low voltage. In the cable each strand is placed around the surface as its neighbor is placed. Corona starts at a very high voltage because each strand shields its neighbor and the stress is divided equally between them. If, in the process of manufacture, one strand becomes squeezed out so that it stood above its neighbors it would take more than its share of the stress and local loss would occur at a lower voltage.

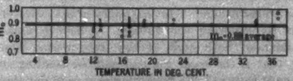


FIG. 4—M_0 VALUES—IRREGULARITY FACTOR OF THE CABLE SURFACE

Data taken from Table I—*Electrical World*, May 6th, 1922, also included Fig. 26.

Points indicated by x are bad weather points divided by an assumed average bad weather factor, m_s = 0.95 to reduce to m_0.

Points indicated by o are fair weather points calculated from data given in the table.

Points indicated by △ are points calculated by Mr. Wood where they do not agree with the x or o points.

x Storm points in table divided by m_s = 0.95.

o Fair weather points from data in table. $m_0 = \frac{m_s m_0}{m_s}$

△ Given when Mr. Wood's calculations do not agree.

In conclusion I wish to again express my appreciation of this paper and to point out that it further confirms our belief in the success of 220-kv. transmission.

R. J. C. Wood: Mr. Peek's criticism of the use of the symbol capital M_0 to include the combined effect of surface roughness and weather conditions is well taken. It should be remembered however that the whole investigation was primarily undertaken to determine the constants of a definite line already built in a definite location, and that for this purpose the single factor answered the purpose. Sufficient data are given so that those interested may further split up this factor as desired.

There seems to have been some misunderstanding of Fig. 26 and 27. Fig. 26 gives the results obtained experimentally while operating at 161 kv. to neutral. The observations were taken every two hours, and from the measured loss, the physical constants of the line, and the atmospheric data, that value of M_0 was determined which would in each case satisfy the other conditions. A casual glance at the plot of M_0 against temperature shows that the two increase and decrease together, although the air density factor has already been allowed for in the calculation of M_0. The diagram is somewhat of the shot gun variety, and had average values of M_0 for each degree Centigrade been plotted a much better looking result would have been obtained but at a sacrifice of sincerity. In Fig. 27 values of M_0 are plotted after having been determined from observations taken in both clear and rainy weather while operating at 141 kv. to neutral. No claim is intended that these values of M_0 bear any relation to temperature in fact the diverse weather conditions would preclude such an idea at once, but; for comparison, the line of Fig. 26 is extended through Fig. 27 as an indication of what might be expected to be the values of M_0 *in clear weather* at the lower temperatures, and to show the extent of the deviation from the fine weather line, caused by rain.

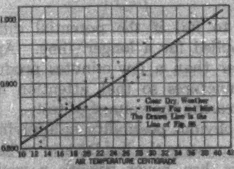


FIG. 5—OBSERVED VALUES OF M_0. 19.5 AND 12 MILES OF LINE, 161 AND 156 KV. TO NEUTRAL, 50 CYCLES

In Mr. Peek's replot of Fig. 27 in his chart No. 3 he has compressed the vertical scale so that a direct visual comparison of the two charts is difficult to make. His suggestion that the low temperature observations in his Fig. 3 are probably due to moisture is I believe not tenable as in this country such temperatures as 2 deg. cent. are only obtained with clear skies and unimpeded radiation.

Since reading Mr. Peek's discussion I have gone over the original data very carefully, together with U. S. Weather Bureau reports, and have selected a number of observations about which there is apparently no doubt as to absence of fog and including readings upon 12 miles of line taken at high temperatures. These are plotted in the accompanying Fig. 5 as clear circles. In the same figure are plotted a number of observations taken in heavy fog and mist but not rain, these showing in full circles. Apparently there is no discontinuity between the fair and foggy weather data and this would indicate that it is temperature and not fog that determines the variations of M_0 for this line.

In most of the published data upon corona loss measurements a suitable value of M_0 has been chosen and the loss, as calculated assuming this M_0 to be constant, shown in the familiar parabolic curve, observed losses have then been plotted lying more or less along the curve. The value of M_0 is chosen so as to place the calculated line well through the observed points in the upper part of the curve at high voltages, and the lack of agreement at below the visual corona point assigned to the dark realms of probability.

From a practical standpoint it is precisely the sub-visual region that is the most interesting. A transmission line cannot be expected to have a corona loss in accordance with the quadratic law until there is sufficient corona upon it to smooth out its roughnesses and this seems to be at about the visual point. This is illustrated in Fig. 6 in which is shown the observed losses of the test of Oct. 12, the data being in Table VII. The drawn lines show calculated losses, first assuming the whole line to have an irregularity $M_0 = 0.85$ which agrees well with the observed data above the visual point, and secondly assuming three tenths of the length of the line to be in corona with a factor $M_0 = 0.78$ which agrees with the observed losses below the visual point.

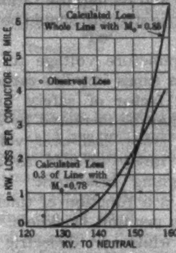


FIG. 6—CORONA TEST, 19.5-MILE LINE, 11 DEG. CENT., BAR. 72 CM. 50 CYCLES, OCT. 12/21

It seems logical to conceive of the line as having certain portions rougher than others and consequently having a lower value of M_0.

It should be remembered that in all the calculations of this paper the mean logarithmic spacing of the conductors has been used equal to 1.26 times the spacing between adjacent conductors. If on the contrary the spacing between adjacent conductors be used in the calculations, larger calculated values of charging current and higher values of M_0 in the corona formula will result.

An Overpotential Test for Insulators

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Some of the factors met in the design of insulators and characteristics of routine electrical tests are discussed in this paper.

A new overpotential test is described with its application and effects. Results of this test make possible a higher standard of practise in the manufacture and use of transmission line insulators.

Ever increasing responsibility is being placed upon transmission line insulators. To establish by specific tests that each insulator put into service has a liberal initial factor of safety and further to be assured that the insulator will be proof against deterioration in service is the ideal toward which we are working.

FACTORS IN DESIGN

PERMANENT high dielectric strength in an insulator is the fundamental requirement, but this is not an independent factor in the determination of sound insulators. Along with dielectric strength we must consider the flash-over voltage of the insulator, its shell thickness and its impulse ratio. If these three be high the dielectric strength should be correspondingly higher.

The ratio of puncture voltage to the product of flash-over voltage times impulse ratio may be taken as the electrical factor of safety in service. This factor of safety may be increased by higher dielectric strength and by lower flash-over voltage, while the impulse ratio is rarely utilized as an independent variable in designing insulators. Higher dielectric strength in turn is a function of thickness as well as dielectric strength per unit thickness. Thickness is a matter of design while unit dielectric strength in the case of porcelain insulators, is contributed by effective solution of the ceramic problem. These two factors may appear to be independent but they are, as a matter of fact, strictly interdependent. Thicker insulators have replaced the thin sections of former days, but unless this increase in thickness is accompanied by better porcelain, the sought-for increase in dielectric strength is but temporary. The thicker the porcelain, the more necessary it is to prove its soundness.

Thicker shells of good material are better. They are stronger mechanically and more quiet electrically. But what shall tell us that they are not of a quality whose inferiority is hidden by the thickness of the shell? The electrical test is the only practical means of proving each insulator.

ROUTINE ELECTRICAL TESTS

The routine electrical test is depended upon to weed out poor material. The potential of this test as usually applied, is flash-over voltage. The potential required to puncture a piece of good quality may run twice the voltage of flash-over. Some insulators fail on flash-over test. Those that pass the test, range in dielectric strength between flash-over and the puncture strength of sound porcelain. Some insulators that pass this flash-over test have inherent weakness that would cause them to fail if the potential difference were higher or applied for a longer time. Application of voltage longer than a few minutes produces but few additional punctures so that attention has been devoted to increasing the voltage of test.

The most obvious possibility of applying higher potentials is to immerse the insulator in oil as in puncture testing. This has never become a routine test on insulators for service because of its many disadvantages. On account of the presence of this medium of low dielectric constant and high dielectric strength the application of full potential is limited to areas actually in intimate contact with the conducting terminals. This restriction localizes and intensifies the dielectric flux to such an extent that damage may be done to perfectly good insulators. Aside from this, the immersed oil test is expensive to apply.

Two other tests that have had commercial application in routine testing of suspension insulators, secure a slight excess of voltage above 60-cycle flash-over by utilizing the impulse ratio or the time lag of the insulator. They are known as the high-frequency test and the impact test.

THE HIGH-FREQUENCY TEST

This test employs damped wave trains of the order of 100,000 to 200,000 cycles a second applied for a few seconds. The vigor and time with which this test can be applied are somewhat limited by the tendency of the flash-over streamers to become localized and then to start digesting the porcelain by local heating. The detection of a small percentage of unsound material that the 60-cycle open flash-over test would have allowed to pass has heretofore justified the use of this test. It cannot be relied upon for the detection of the greater part of material that is improperly fired nor for many checks that escape visual inspection.

THE IMPACT TEST

In the electrical impact test a spark gap in series with the test causes a slight amplitude of damped high frequency to be superimposed upon the low-frequency wave.

A condenser across the line adds to the slight surge of high-frequency energy when flash-over of the auxiliary gap occurs. The intensity of this test varies with the energy available from the source and from the

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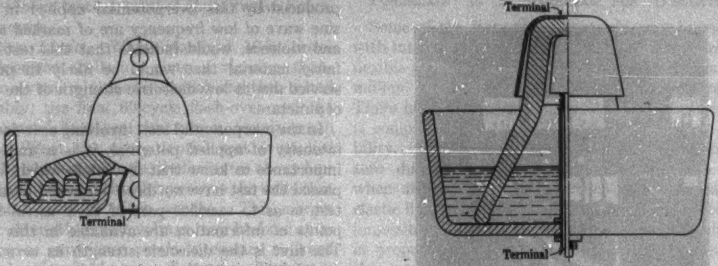
Presented at the Pacific Coast Convention of the A. I. E. E., Vancouver, B. C., August 8-11, 1922.

condenser and depends upon a nice proportioning of the electrostatic capacity of the auxiliary gap to the capacity of the insulator, and is further affected by the resistances in the circuit. If the capacity of the gap is too low the insulator charging current leaks across the gap too early to cause much high-frequency amplitude to remain on the crest of the 60-cycle wave. If the capacity in parallel with the auxiliary gap is too high, the insulator flash-over starts at normal frequency and the impact effect is lost again. The impact effect is greatest with an auxiliary sphere gap discharging just before the low-frequency voltage wave reaches maximum value. As the possibility of utilizing the impulse ratio of the insulator in commercial routine testing depends upon the electrical constants of the circuit, a standardized test of this nature is not readily attained and verified.



FIGS. 1 AND 2—ARRANGEMENT FOR OVERPOTENTIAL TEST

At best, either the high-frequency or the impulse test adds but a few per cent to the voltage available to test the dielectric strength of the insulator. It must be assumed that voltage surges in service will equal in intensity any test voltage depending for its added effectiveness upon the steepness of its wave and the time lag of flash-over. Such tests cannot raise the minimum factor of safety above unity, much less establish a definite margin of safety or weed out insulators that may deteriorate in service.

THE OVERPOTENTIAL TEST

To make it possible to test insulators at any definite voltage desired from flash-over to high puncture, the following overpotential test has been devised and used for commercial testing. In this test (Figs. 1 and 2) the insulator is placed in an insulating dish which holds a sufficient depth of oil to form an electrical flash-over seal at the rim of the insulator at the same time leaving the head and center part of the shell exposed to the air. The inside terminal is connected with a conductor passing up through the center of the dish. In effect the dish becomes part of the insulator which temporarily, for testing purposes, acquires an extended flash-over distance, sufficiently long to prevent flash-over at the chosen testing voltage.

Application of the Test. With the above simple arrangement many possibilities at once appear. On account of the presence of air inside and outside, the vital center of the insulator is bathed in active corona (Fig. 3) which diffuses the potential without concentration and without local heating and injury to the insulator; although covered with this ionized air the temperature of the insulator at the end of test is not hot. The area exposed to active potential may be limited as desired by raising the oil level.

On account of absence of flash-over (see spark gap, Fig. 4), the specified test voltage can be maintained at a constant value by holding a fixed voltmeter reading showing potential impressed upon the primary of the testing transformer. This value can be verified accurately at intervals by checking against the spark gap without the disturbing surges that accompany calibration with parallel flash-over. Either the sphere gap or needle gap can thus be used to calibrate the test without the discrepancies that usually attend the determination of flash-over voltage by means of these two

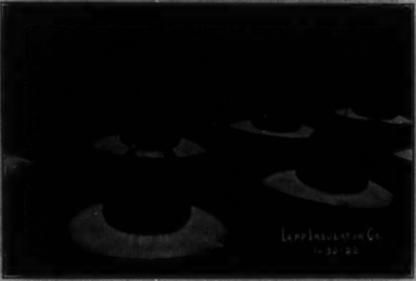


FIG. 3—OVERPOTENTIAL TEST—CENTER OF INSULATOR BATHED IN ACTIVE CORONA

gaps. Not only will the surge from a flash-over test cause the gap to discharge and vice versa, but the sphere gap is more sensitive than the needle gap and usually more sensitive than the test to this voltage kick because of differences in impulse ratios. By eliminating flash-over we eliminate the indeterminate effects noted and make it possible to apply to the insulator an accurately determined voltage of approximately sine wave. The importance of applying low frequency may be gained from an observation of the effects of the "high-frequency" test. It appears that the surface digestion of the porcelain is due to a lack of penetration of the dielectric stress deep enough to cause a uniform potential gradient throughout the thickness of the dielectric. It appears that the energy per half cycle of the damped high-frequency wave is not sufficient to supply the energy required by dielectric hysteresis and to overcome the counter electromotive force due to time lag of the dielectric in giving up charge except for the surface of the insulator which is immediately in contact with the rapidly reversing potential. The fact that continuous waves of the same order of frequency heat the dielectric many times more rapidly than this damped wave train test, indicates the degree to which the energy is curtailed. This phenomenon may be compared with the skin effects in a solid electric conductor which make the body relatively impenetrable to high-frequency electromagnetic induction.

LAPP INSULATOR Co

Fig. 4—Overpotential Test—Spark Gap

By confining the high-frequency energy to the surface of the dielectric, destruction proceeds piecemeal through thermal expansion and spalling of the affected region, rapidly taking advantage of the initial local or superficial difference in dielectric strength and accomplishing a puncture only by a process of progressive destruction. This type of failure requiring several thousand successive cycles for its completion, does not appear to correspond to the line failures caused by surges or by lightning as these latter seldom show evidence of progressive digestion of the porcelain. Such line failures are probably completed by a few cycles of high energy which shatter the dielectric by applying a fairly uniform potential gradient to insulators of weakened dielectric strength.

Results of the Test. The fact that the punctures produced by this overpotential applied in a smooth sine wave of low frequency are of marked suddenness and violence, would indicate that this test eliminates fairly material that would be likely to puncture in service due to low dielectric strength of the total path of puncture.

In the overpotential test, involving as it does a higher intensity of applied potential, it is a matter of first importance to know that insulators which have safely passed the test have not been weakened because of the test so as to sacrifice part of their useful life. Two points of information are available in this condition. The first is the dielectric strength as actually determined by puncturing under oil insulators that have passed the overpotential test. The curve of distribution of punctures as obtained on the test itself provides the second source of information. (Fig. 5.)

From records of puncture under oil of 1 per cent of several thousand suspension insulators, representative of six months' production, minimum and average puncture values were increased about 20 per cent and 15 per cent respectively, above previous values on similar units tested by liberal flash-over with impact. Maximum values of puncture were fully as high after applying the overpotential test. In no case was an oil puncture value below the overpotential used on the test.

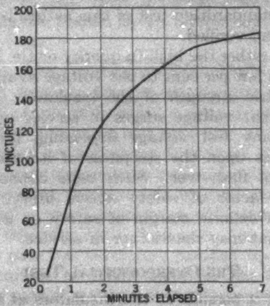


Fig. 5—Time Distribution of Punctures—Overpotential Test

10-in. suspension insulators. Potential applied 125 per cent of flash-over. Time of test, 5 min.—2 min. after last puncture.

The curve (Fig. 5) giving distribution of punctures throughout the five minutes of test shows that two-thirds of the failures occurred in the first and second minutes of test and failures diminished in succeeding minutes, indicating that at the voltage of test no evidence of dielectric fatigue had appeared. If the time of application were to cause increasing loss this curve would show a tendency to rise again. For the purpose of securing further data on the effects of time and intensity of voltage application, a few units were left through successive tests, a total of about twelve hours, without puncture.

Specification Limits. When standard 10-in. uncemented suspension shells are given a vigorous flash-over test for several minutes as is usual, and then tested after assembly, the final 60-cycle flash-over and the "high frequency" together puncture a certain small percentage. When the overpotential test is applied instead of the above final tests, it eliminates about four times as many units and thereby removes the units that would be most likely to fail in service. This margin of dielectric strength or test voltage may be fixed at as high a value as experience proves necessary to weed out material not reliable as a dielectric. The exact value to which it may prove economical to limit the test voltage will be determined by a balance between the cost of failures in service and the cost of insulators of the grade specified. That point can be worked out and a definite standard of dielectric strength established on as sound a basis as engineers are accustomed to use in the purchase of steel for example. The point is that this overpotential test makes possible a definite specification and a means of fulfillment. With a knowledge of the kind of material that goes up on the line, we have a definite starting point for service records.

DESIGN VERSUS MATERIAL

It may be objected that the foregoing lays too much stress on dielectric strength and overlooks matters of design and structural details that have undoubtedly been the cause of some failures of insulators. While this problem of design is important, specific information is available for its solution. Physical failures other than dielectric may be classified as to type and definite provisions made in the insulator structure to correct the trouble. Given a porcelain insulator of tested high dielectric strength, the permanence of its electrical and mechanical characteristics is also assured by the same test. For such porcelain coefficients of elasticity and thermal expansion become stable. Design tests for mechanical strength run fairly uniform and liberal factors of mechanical safety can be employed. Few purely mechanical failures are experienced on account of external loading. Insulators of stable dielectric material, with adequate provision for differential thermal expansion and contraction, do not fail in service.

Differentials within individual shells as well as between the shells and the metal and cement composing the structure, should be considered in compensating for temperature variations. Stresses within the insulator can be kept well within the strength of the porcelain with a good margin of resistance to meet external service loads. When porcelain is fairly treated in design with due regard to its known characteristics, it attains a high order of reliability.

PORCELAIN AS A MATERIAL FOR INSULATORS

Some of the facts about porcelain may be recalled with interest. Within its strength it is three times as flexible as steel since its elastic coefficient is about ten million. Its yield point is also its ultimate strength. There is no permanent elongation. In this particular it compares very favorably with the metals in reliability. When the metals approach the condition for zero ductility they become very unreliable. Steel when alloyed or treated to such a degree that the elastic limit approaches the ultimate strength, becomes impossible to handle without cracking. Reliability is in proportion to ductility of the metal. Porcelain in this respect is of superior toughness because of its thorough anneal and its flexibility.

By taking advantage of its characteristics, the very limitations of porcelain may become a source of strength. A rod of porcelain is a case in point. Values of modulus of rupture in bending for moderate-size rods are observed to be twice as high as values of ultimate strength in tension. This is about the same ratio as found in cast iron and is due to analogous causes. In both cases segregation of density occurs to some degree in the forming process. Skin friction in the die from which the clay is extruded and in the mold through which the iron flows, slightly differentiates the surface from the interior material. In the subsequent shrinkage of the cast iron when it solidifies and in the shrinkage of the clay as it dries, and later as the clay is fired, and further as it is cooled, all of the changes progress from the outside to the inside, accentuating the initial differentials and leaving the rod with a shell under compressive stress and the center volume in tension in all directions. It is now readily seen that when such a rod is stressed in tension, a value lower than the true strength is obtained because part of its strength is cancelled internally. When stressed by bending, the initial compression in the side opposite the load, reverses to a tension stress only after the load has caused flexure, and at the instant of rupture the greater part of the area of cross-section is under tension while the neutral axis is shifted to the compression side. As porcelain is many times as strong in compression as it is in tension, this means favorable loading and an unduly high value of modulus of rupture is found.

The above case of the rod is discussed at some length to illustrate in a quantitative way, the cause and effect of internal stresses. This simple case may give some idea of the value of careful design and indicate why some designs must fail. The hazards accompanying increase in thickness may be appreciated to some degree by this analogy between porcelain and cast iron. Sound cast iron is made and relied upon; sound porcelain can be made and relied upon in designs that respect its properties.

Porcelain now has this advantage, its soundness as a dielectric and to a great extent, the permanency of all its qualities can be tested by the application of a sufficiently high potential and this can be accomplished without deterioration of what strength it may possess.

CONCLUSION

Meeting the increasing demands for reliability in transmission of power, a test has been developed which applies to an insulator a definite chosen potential in excess of its highest normal flash-over voltage.

By the elimination of doubtful material, the minimum factor of safety of the insulators can be raised to a point where sound dielectrics are assured.

This test gives to the purchaser a definite basis for specifications and a means of attaining a higher duty insulator.

It gives the operating engineer a knowledge of what grade of insulators he puts on his line—a basis for service records that will mean something.

In this test the manufacturer will find a spur to progress and a proof of quality.

Discussion

C. E. Skinner: Porcelain is essentially in effect a conglomerate of spar, flint and kaolin. Each individual piece has its own personal history. A very large number of factors inevitably enter in, to affect it for good or ill in its making. Much can be done by the ceramist and by the porcelain factory to insure uniformity, but the day will never dawn when lots of porcelain insulators can be tested by sample as we test steel and many other materials. We must always test each piece to see that that piece does not have accidental defects and weaknesses that would unfit it for its intended service. What is required is a test that will search out such defects and weaknesses and which will leave the piece uninjured by the test itself. It is up to the porcelain manufacturer to so operate his plant that he secures the maximum of uniformity, and the test should eliminate all pieces which fall below an agreed standard. The agreed standard should be that which gives satisfactory service under the prescribed conditions. As no test can duplicate service conditions—in fact probably no series of tests can duplicate service conditions—the combined experience of manufacturing, testing and service will finally show what balance should be struck between severity of test and service. We can so test that we destroy every insulator, then we have none for service. The most careful manufacturer cannot hope to so fabricate that no test is required, so there must be an economic balance between test and service. We all welcome any test that will help to show us whether design and material are right, and any test that will eliminate insulators which would not give service.

Mr. Lapp's test is one which should aid designers and manufacturers in determining whether design and material are right, and possibly may be justified in certain cases for a routine test where conditions are unusually severe. I very much doubt, however, if this test will entirely eliminate insulators which would develop flaws or faults in service, and particularly those which may be due to mechanical stresses.

I think the test is one that we should all welcome and give a thorough trial. It will not be an easy test to carry out on large numbers of insulators.

C. L. Fortescue: Mr. Lapp seems to have made out a very good case for the method of testing insulators which he advocates. However, he falls into some errors in his anxiety to make a case for this type of over-potential test. In high-frequency tests for example, the applied frequency as he says, is damped trains of the order of 100,000 to 200,000 cycles a second, but the actual frequency of the test to which the insulator is subjected may be many more times this frequency for the reason that flashover of the insulator sets up another train of damped oscillations which are superimposed on the impressed train. The severity of the high-frequency test is due to the fact that for each half cycle of the 60-cycle current supplying the high-frequency set many more damped oscillations of the natural period of the insulator occur than in the case of the 60-cycle flashover test. However, there is, as Mr. Lapp remarks, a question if such a test may not cause damage by the heating due to the high frequency localized stresses, which are incidental to such tests, and therefore, it becomes necessary to limit such tests to a comparatively short period, as compared to the 60-cycle routine test.

In the 60-cycle routine test the actual 60-cycle applied voltage is not the time test voltage, but the flash-over of the insulators superimposes a highly damped train of oscillation at every half cycle which raises the potential to a value considerably above its normal 60-cycle flashover of the insulator. In order to obtain the best results with this test the impedance of the transformer should be at the proper relation to the capacity of the low and the applied frequency. When this condition is approximated this method appears to be a very reliable routine test for insulators.

The overpotential attainable is, as Mr. Lapp states, limited by the impulse ratio of the insulator, but so too is the impulsive stress to which the insulator is subject under operating conditions Indeed, if we would make a true comparison we would find that, if anything, the potentials to which the insulator is subjected under routine test are several times more severe than any surge they are likely to get in service.

Puncture tests under oil indicate that the 60-cycle routine test, when properly carried, weeds out all the insulators which are likely to be a hazard under operating conditions.

The impact test is a very useful test on insulators also. In this test a large condenser is shunted by the insulator or insulators it is desired to test in series with a sphere gap. The latter is set to a setting somewhat greater than the flashover setting for the potential it is desired to impress on the insulator. The condenser terminals are connected to the terminals of the 60-cycle transformer and the voltage across it is raised until the sphere gap breaks over. It is essential in this case that the capacity of the sphere gap be small compared to that of the insulator, otherwise the initial flashover may take place across the insulator. There is, however no difficulty in obtaining proper operating conditions. The main difficulty is in determining the value of the impulse to which the insulator has been subjected. There is also, in this test the same danger which Mr. Lapp mentions of the arc localizing along a certain path, and melting the porcelain.

Mr. Lapp is, I think, in error in his assumption that the voltage surges to which an insulator is subject in service will equal in intensity the values obtained on test. It is quite possible to obtain conditions on test many times more severe than any that can be obtained in service.

Regarding the test recommended by Mr. Lapp, it has many good points in its favor. One is that the insulators are not flashed over and the testing equipment will not have as severe service as in the case of flashover. Another is the absence of the deafening noise accompanying flashover test, and the presence of large amounts of ozone which tend to produce headache.

A good feature of the method is that the value at which the test is made is under control. In the general run of suspension insulators, a certain test value may be found economic. For special requirements, a higher value may be necessary and for such cases, the batch may be taken from the standard batch by eliminating those insulators which fall below the test requirements. So far this is very good, provided that the purchaser of the special insulators agrees to pay a special price for his selected insulators. Otherwise, the purchaser of the standard insulator will have to bear part of the cost of the losses sustained in selecting insulators for more exacting service.

I think it very doubtful if this method of testing will be of any advantage for any other type of insulator than the suspension type. There are certain features in this method which make it very good when applied on a small scale, but on a large scale, there would be many disadvantages. The handling of large amounts of oil in vessels exposed to the air is, to say the least, unpleasant and may be hazardous unless the testing is done in an isolated fire proof building. Altogether, I feel that while electrically the method presents some good aspects, it should be carefully investigated before it is adopted.

It should be understood by all concerned that more severe requirements will most assuredly lead to more costly insulators. This may, of course, be economically justified, but it is well to point a warning so that the purchaser will realize that he is not going to get something for nothing.

Mr. Lapp knows that equally as good elimination up to a certain point may be obtained by methods in vogue. Whether a higher elimination will be justified is a question which depends on the worth of the increase in reliability to the user, because such elimination will certainly increase the cost of the insulator to the purchaser.

Lastly, there is some unpleasantness associated with the use of oil in testing insulators which, while not of paramount importance, makes it desirable to find something more convenient to use.

E. E. F. Creighton: Some of those present may not know that I started the oscillator test some years ago, and I have been waiting a long while for people to take it up. Now there are good reasons for that, the principal reason being that the main trouble with insulators could not be corrected by any of the electrical tests that we had in mind. The main trouble—ninety-nine per cent you might say, or maybe it is ninety per cent of the troubles—came from moisture in the porcelain. The moisture I should say in the cement causing a deterioration in the porcelain, and most of that deterioration was due to the absorption of the moisture.

That perhaps is not the major trouble; but the expansion of the cement itself. Cement has a property of expanding, as civil engineers have shown us, continually, if it is moistened and dried. Every time it is moistened it expands, every time it is dried it contracts; every time it is moistened again it expands a little bit farther, so that each time it gets thicker and thicker, until finally it so fills the space between the pin say and the porcelain, or between one porcelain shield and the other, that the natural temperature expansion will cause a crack in the porcelain.

Now as a matter of fact part of the trouble in recent years has been due to this expansion effect. Naturally, the test will not show that. There is a perfectly good porcelain insulator, when it leaves the factory, that has been broken by temperature effects. That fact, however, does not detract in any way from the desirability that Mr. Lapp has emphasized here of an over potential test. When we get rid of the large number of the troubles due to expansion of cement, then it seems to me it becomes necessary to make refinements of over-potential tests.

As Mr. Skinner has pointed out, any sort of test is going to eliminate—any sort of severity in test is going to eliminate more porcelain, and it has to be paid for; but I think it is a very good investment. The whole question, which has been under discussion for years, is what is a reasonable, proper test. The nearest we can come to it in my estimation is to say what are the strains put on an insulator in practise. The principal dielectric strain comes from lightning. Lightning may be of low frequency, but it is more liable to be of high frequency, therefore some transient test, or some continuous test with the higher arc-over value should be applied—some continuous test which is equivalent to a transient test.

The nearest I could see to the proper test was to apply a very sudden test, either by the oscillator or by the impulse test, which would be equivalent to lightning. There has been discussed many times the question of whether it does not damage the porcelain. Just to conclude the matter, compare this situation, an insulator that is tested equal to arc-over value, that porcelain, at the instant that the test ceased, may be at the point of puncture. It has been damaged, it would have punctured, say if the test had been continued a few seconds longer; therefore, there is a piece of porcelain that is damaged and put on the line. Now consider the over potential test, a test at say twenty per cent above arc-over values. That insulator may also be just ready to puncture when the test is stopped, but you have that factor of safety, enough to protect the insulator from lightning.

It seems to me therefore, that, finally, the standard test will be some form—and it does not make any difference to me personally—of over potential test as a perfectly proper test to put on the insulator.

C. P. Osborne: This matter of insulators to the operating men reminds me of the small boy who didn't know which school he wanted to go to. We will have four or five different salesmen come into our office and each of them will tell you the advantages and disadvantages of his insulator. One will tell you that porcelain must be thick, the next one will tell you it is in design, the next one will tell you that the curve is not just right—and the operating man is up in the air. I have been attending these conventions for about ten years, and as yet I don't believe the manufacturers agree on types of insulators. Of course, each manufacturer has his own ideas of these things, and each is the best according to his own ideas.

I have had considerable experience with insulators in a country where we have no salt air, but we have great differences in atmospheric conditions—a great deal of rain, then sunshine, then fog (of course it only rains once in a while in Oregon); but we have had considerable trouble with different types of insulators in our operation, and it seems to me that manufacturers and operating engineers are not close enough together. It is a serious problem. Right now we are endeavoring to build a line, and the economic question in building the line is what type and form of insulator to use. We have to calculate the cost from many angles to arrive at the economic figure for this. You can go to an expense which would be prohibitive. The operating man has to keep his expense down. The manufacturer must manufacture something that the operating man can afford to use, but the manufacturer must charge a price at which he can deliver an insulator that will give the operating man service. Service is the first thing we must get. Public service corporations are simply the tools of the public; you cannot give the public an excuse for a shutdown. They are educated to the point where you must give them continuous service, and when an insulator breaks down it is the least of their troubles. We can say, well the manufacturer thought he had insulators that would not break down. Of course, several reasons might cause the insulator to break down. The boys might shoot it, for instance; and sometimes small checks in the enamel will occur which allow moisture to get into the porcelain. These checks may not be visible to the eye without a magnifying glass. The reason for this I do not know. I don't want to place the blame on any one manufacturer; I find it on most any insulator we have, and we have several different makes.

I do feel that there is not enough cooperation between the operating man and the manufacturer. Somehow it seems to me that a change ought to be brought about through closer study of operating conditions. It is the same thing in operation as it is in manufacture. It may be that no two operating men will agree on the same subject; but we are vitally interested in this insulator game. I do feel great strides have been made in the manufacture of insulators in the last few years, and I am beginning to feel the weak spots in our system are not so much on the line as formally.

R. J. C. Wood: If it can be proved that we are going to get better insulators for the money, the proposed method of testing will be justified.

I agree with Mr. Fortescue as to the statement of Mr. Lapp that we will get surges in practise more severe than the highest test we would ordinarily put upon an insulator. If such a condition existed I would consider the line to be under insulated.

The whole matter is a question of economics. We will pay extra money for good insulators just so long as we get our money's worth and no longer. We have had some small experience with this testing device of Mr. Lapp's. They sent us out some of the porcelain to test and we tested a number of insulators. Many of the punctures that we got with this method of test were some little distance out from the cap, approximately half way between the cap and the outer diameter of the porcelain. Presumably, as Mr. Lapp suggests, the insulator was not designed for this particular form of test, and to meet the more severe condition imposed by this test the porcelain would have to be thickened out towards the edge of the insulator. Whether that would actually be required to take care of the stress that occurred normally on the line, I rather doubt. It might be putting material in a place where it was not necessary on account of line stress in order to make it pass this particular, special test. However, another few ounces of clay in the insulator does not amount to anything in the matter of cost. There has been a good deal of talk in the past as to the possibility of damaging an insulator by subjecting it to excess electrical tests—and presumably a feeling that an insulator can be tested with a certain potential of less than puncture value with resulting damage. Perhaps some of those present can tell us the nature of that damage, what it is that happens in the porcelain that takes some time to come to fruition.

On the Big Creek lines we have got quite a number of insulators —there are some 7000 towers, suspension towers with twenty-seven dead-end towers with one hundred and thirty-two insulators on each; and there is a great percentage of those dead-end towers, so there are a great many disks on the line. We have kept records of every individual insulator that is meggered and its location in the string on each line, each phase, *a*, *b*, and *c* on each tower, and the date and a few other things. All these data were taken for the last three years and punched on cards; then run through the machine and the information segregated in any desired manner.

The analysis of insulators that show low on the megger shows that in the suspension strings a vastly greater percentage of the top units proved bad, the ones nearest the tower. The first thought was, that in Southern California the sun which shines there has been shining on these top units on and off every day of course, and expanding and contracting them, and that is the reason why they have failed so much more than any others in the string. But we found that in the dead-end insulators which lie in a horizontal plane and all get the sun alike and the same thing is true, it was the one nearest the point of suspension at the tower which proved bad in the greater percentage. The one showing the next highest percentage was the one next to the conductor. Of the others there was nothing to pick, they all showed about an equal percentage of failures.

This at once began to have the ear marks of a mechanical failure. There is a good deal of vibration on these lines, and it was a sort of crack the whip performance, the one nearest the tower took the brunt of the shock. It seems that there is a great deal of room for research on the strength of porcelain and insulators under repeated alternating stresses. We are starting some work on this latter phase of the question and rigging up a small span about twenty-five feet long with a dead-end insulator at one end similar to the insulators on the Big Creek line, with a tension arrangement on the other end, so that this twenty-five feet of cable may be stressed to the same amount as the actual line. A motor driving an eccentric connected to the centre of the span will keep it in violent vibration back and forth. We hope to discover whether such a vibration has any effect upon any insulator, and whether it picks out the ones nearest the point of support in the same way that often happens on the line. If so, we will have started on the road to discovery of some of the causes of most of these failures.

There is need of an insulator of greater mechanical strength so that we can increase the size of our conductors. The amounts of power now transmitted are becoming so large that the corona limit is not going to be the determining factor in the size of a conductor but we will go above the corona limit of size in order to cut down line loss. And this all ties in with the question I raised before, as to whether it is not a mechanical weakness that is responsible for the greater part of these insulator failures.

Alan W. Eshelby: Mr. Wood has asked the question "What happens during the flashover?" I don't pretend to stand here and tell you what happens, but I would like to suggest a possible means of finding out what happens during the flashover. To the best of my knowledge, the method I will describe, is not in use commercially at the present time.

I have been interested for a number of years in photography and it occurred to me that the use of quartz in the camera in place of the glass lens might be of some advantage in photographing incipient corona. I therefore had such a lens ground and equipped my camera with it, but as I was not in a position to make standard laboratory tests I had to be content with taking photographs of flashovers on generators in actual service. I made these photographs using two cameras. One camera equipped with a standard Jena glass lens, the other equipped with a lens ground from natural rock crystal. Both shutters being arranged to operate simultaneously. In practically every instance there was no similarity in the photographs.

Quartz as you know, is transparent to the ultra violet end of the spectrum, while glass is absolutely opaque. The photographic emulsion is more keenly sensitive to the ultra violet end than the visible end. In fact the ordinary photographic emulsion is sensitive from approx. 3250 Å to 6000 Å and certain special emulsions have even a greater range.

The Westinghouse Company has developed for use in special tests, a high-speed camera which takes a series of photographs rapidly succeeding each other (not a motion picture camera) all exposures being made on one plate, unfortunately Mr. Legge, who designed the camera, has used a very cheap achromatic lens in this camera and I feel that here is a case where the quartz lens would tell an entirely different story. To those who are interested and wish to experiment along those lines let me suggest that they use natural rock crystal and not synthetic quartz, remembering that the speed of quartz is approx. seven times that of glass.

W. D. A. Peaslee: There are several points in Mr. Lapp's paper with which I believe it is necessary to take issue. The first sentence of his second paragraph is a little bit misleading, as he has not specified the frequency of flash-over voltage, or the frequency at which the impulse ratio is taken; obviously it would not be correct to use a flash-over and impulse ratio, taken at different frequencies in this way.

The last sentence of this second paragraph I agree with most heartily and believe that it cannot be too strongly impressed upon the manufacturers and users of porcelain insulators.

In regard to his remarks about the effect of immersing the insulator in oil for testing, I believe he has omitted the most important result of such an immersion; that is that the different dielectric constant of the oil distorts the flux, the dielectric flux producing an entirely different distribution over that encountered in air. On page 492 he makes the statement that the high-frequency test adds but a few per cent to the voltage available to test the dielectric strength of the insulator. I believe this statement is entirely unwarranted, as my experience in a good many years testing in this particular field, indicate that an increase in the neighborhood of 30 per cent can be so secured under constantly stable conditions.

The overpotential test discussed by Mr. Lapp is not at all new and while I do not know who originated it, I do know that it has been known to advanced workers in this field for ten years or more and has been abandoned by some of them for rather definite reasons, most important of which are that it protects the petticoats of the insulator from the searching effect of a high-frequency test and that it distorts the field around the insulator, making the test not at all representative of the conditions under which the insulator will be forced to operate on the line. I believe it is fundamentally wrong to run a routine test on any apparatus that is radically different in conditions from those which it will encounter in practical operation.

I am very much amazed at his statement that the insulator does not get hot under this test; as my experience of this test a good many years ago indicated a rather decided rise in temperature of the samples under test.

I am also very much astonished at the claim that the surface digestion of porcelain is due to a lack of penetration of the dielectric stress. I believe that it can be conclusively demonstrated that this digestion is entirely a temperature effect and is due to the extremely high temperature of the corona streamers. I cannot conceive of any lag in the establishment of the dielectric field of an order of magnitude necessary to make this claim substantially correct and I believe that the heat absorbed on sustained high-frequency stress, is entirely an energy function, due to the characteristics of the porcelain as a conductor of the third class wherein the current voltage characteristic changes from a positive to a negative value at some particular current density. I do not believe the data available warrant the assumption that this phenomenon mentioned can be compared with the skin effect in a solid electric conductor. In regard to his specified limits, he states that when the overpotential test is applied instead of the above final tests, it removes the units most likely to fail in service, I would like to ask if he has submitted the units that have received these overpotential tests, to a subsequent high-frequency test, and if so what results were obtained.

I believe that fundamentally there is no such material as a true dielectric of dimensions greater than atomic distances. I can conceive of dielectrics such as a chain of hydrocarbon linkages wherein the displacement of electrons from their attending nuclei within the atom, could be transmitted over the space occupied by several atoms, but as the range of atomic forces is of the order of one Engstrom unit, I cannot conceive of a substance consisting of isolated atoms or molecules functioning as a true dielectric. It seems much more tenable that these insulating materials are conductors having a variable current voltage characteristic, which changes at some point from positive to negative and that their destruction, instead of being a dielectric rupture, is merely due to the fact that the current density has passed the critical voltage point and a further increase of current can result without an increase of applied voltage, or even with an attendant decrease in the voltage drop across the conducting path.

I believe if this theory is applied to the behavior of our insulating materials, a great many of the seeming discrepancies we are accumulating, will be explained and we can appreciate more exactly the fundamental mechanisms of failure of insulating materials under applied voltages.

G. W. Lapp: It is gratifying to hear a note of acceptance of the overpotential test, in principle at least, by most of those who have contributed to this discussion.

Practical economic considerations may set a limit to ones enthusiasm in actually applying such a test to his product but the demand for continuity of electric service should justify higher standards among users of insulators.

Definite improvements in the quality of insulators in the last few years have made it possible now to adopt this overpotential test as a routine test at a slight difference in price.

Among the various points brought out in the discussion no fundamental objection to the overpotential test has appeared.

Mr. Fortescue has noted some of the phenomena of the high-frequency and 60-cycle flashover tests and seems to be impressed with their severity but mentions the difficulty of obtaining values for the impulse effects. Admittedly the deafening and stupefying effects accompanying these flashover tests are extremely spectacular compared to the quiet intensity of a full wave overpotential test but it takes more than noise and ozone to puncture questionable porcelain. It is quite possible to take the units from those spectacular tests and knock out four to six times as many more by applying 120 per cent overpotential.

When flashover occurs on the rise of the 60-cycle voltage wave the heated path of the spark partly lets down the voltage for the remainder of the half cycle. The higher frequency oscillations are superimposed on a lowered base and the few fine peaks that rise from the damped train seem to have small power to puncture porcelain.

In assuming that the insulator in service may be subjected to a condition as severe as flashover test I had in mind a string of insulators with some of the units punctured. Lightning would then cascade the sound units subjecting them to full impulse flashover voltage. Mr. Fortescue has small respect for nature when he conceives that the flashover test is "many times more severe" than such a cascading impact.

Professor Creighton's estimate that over 90 per cent of the troubles in insulators are due to absorption of moisture by the porcelain is in harmony with the conclusion of the excellent paper by Farr and Philpott which is open for discussion. The porosity of porcelain may be due to improper materials, to underfiring or to overfiring and is by far the most subtle factor in insulator manufacture. Porous porcelain may be sufficiently low in dielectric strength to increase the losses by puncture even on the usual flashover test.

The most important function performed by the overpotential test is to eliminate most of this porous material before it is put on the line. As an ultimate safeguard against absorption we glaze our porcelain all over.

The evidence of destruction of insulators because of expansion of Portland cement in the joints is not conclusive. In fact the existence of numerous regularly spaced vertical cracks around the cement joint of pin type insulators appears to give direct evidence of shrinkage of the cement. From an examination of many old insulators including some unbroken glass insulators, through which these shrinkage cracks could be clearly seen, one would conclude that shrinkage of the cement rather than expansion is typical.

One of the insulators examined for these cracks was broken apart exposing the flat top of the second shell the surface of which was pitted because portions of the porcelain had been crumbled off and were found adhered firmly to the adjacent cement. This was an extreme case of disintegration evidently due to absorption of moisture and freezing. It gives some idea of the internal forces that may be present in porous porcelain which help the force of thermal expansion or contraction to crack the piece.

The crazing of the glaze on single fired bodies such as insulators is unusual, when crazing does occur as on dishes it is of a coarse pattern easily seen. It would seem that Mr. Osborne has detected a microscopic form of crazing that has hitherto escaped observation. Even devitrification would not be expected to occur in the type of glass used for insulator glazes.

When Mr. Peaslee comes to witness this test he will be dismayed to see the pittiless manner in which it punctures defects in petticoats and shells as mentioned by Mr. Wood. In fact it is preferable to seal the outer lips of the shell only to save the petticoats from puncturing. It might save years of misdirected effort if some of the advanced workers known to Mr. Peaslee would publish results of their tests.

The very moderate temperature rise exhibited by hard fired disks after several minutes application of 120 per cent of flashover voltage must be due to low losses both within the dielectric and in the corona enveloping the surface. For porcelain having an appreciable power factor the heat due to internal losses on this test is rapidly cumulative to quick puncture because there is no cooling medium as in the immerzed oil test to prevent a rise of temperature. The low temperature of the corona appears to be due to its intensity which causes a high degree of uniform ionization and high conductivity of the air. As the current traversing this low resistance corona is only the small charging current required by the dielectric the ohmic loss is probably very small. By preventing the hot concentrated flashover streamers the major source of heat is eliminated.

A number of units that had passed the over potential test were given the high-frequency test with maximum severity of application without puncturing any of them. The greater number of punctures caused by the overpotential test doubtless includes the same insulators as would be punctured by the 60-cycle and high-frequency tests.

Failure of Disk Insulators on High-Tension Transmission Lines

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THE writing of this article is prompted by the fact, brought out at several Institute meetings at which papers dealing with disk insulators were discussed, that although much successful research laboratory work has recently been done to determine the electrical and mechanical characteristics of insulators of this type, there is available practically no accurate information showing the actual operating performance of such insulators during a period of years. Having recently compiled certain information of this kind I take pleasure in making it available to the profession in the hope that those members who are engaged in the field of ceramic research may find it of interest and possibly of some assistance to them in their work, from which I hope will soon be developed a disk insulator possessing greater mechanical and electrical strength than any such insulator at present available.

The laboratory results of several well known investigators, among whom are Prof. H. J. Ryan of Stanford University, and Mr. F. W. Peek, Jr. of the General Electric Company, have definitely determined the voltage gradient curves and electrical stresses existing in disk insulator assemblies consisting of a number of disks of the same type. Their results show that in an unshielded assembly of seven cap-and-pin type disk insulators with a voltage to ground of 61,000 volts, the voltage gradient curve will be as given in Fig. 1. From this curve we see that the potential drop across the various disks ranges from a maximum of 14,000 volts across the disk nearest the conductor to a minimum of 6500 volts across the third disk from the tower or grounded end of the assembly. Investigation has also shown that the voltage gradient for the third of the assembly nearest the conductor is greater than the gradient for the surrounding air, that of the middle third of the assembly is approximately the same as for the air, and that of the top third of the assembly is less than that for the air. As a result of this condition there is a leakage of current from the disks of the lower third of the assembly to the air, and from the air to those of the upper third.

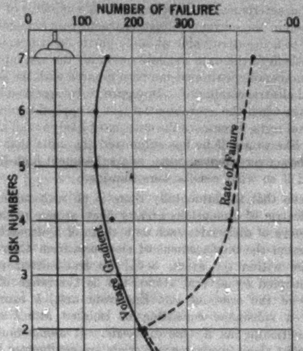

Fig. 1—Voltage Gradient and Rate of Failure Curves for Seven-Disk Assembly, Unshielded
Line Voltage 105,000
Voltage to Ground 61,000

Now consideration of the facts that the leakage resistance is not uniformly distributed along the assembly, and that the various units and the surrounding air are subjected to unequal electrical stresses,

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resulting from the unequal potential drop across the various disks, would lead us to believe that the disk adjacent to the conductor should fail most frequently and that the rate of failure of each of the seven disks in the assembly should bear a definite relation to the intensity of the electrical stresses to which that particular disk is subjected. However, an inspection of the tabulated results given in Table I, II and III, covering nine years of actual operating experience, shows no such relation existing between the rate of failure and the electrical stresses to which the disk are subjected as determined in the laboratory. Indeed these tables show that with the exception of disk No. 2, disk No. 1, the disk nearest the conductor, has the lowest rate of failure in the assembly, and that with the exception of No. 2 disk this rate increases with the position away from the conductor until the highest rate of failure is found for the No. 7 disk this being the one attached to the tower. I would very much like to have someone more familiar than myself with insulator research and high-voltage phenomena furnish a theoretical explanation of the observed results as embodied in Tables I, II and III.

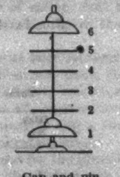
The tabulated results given in the three tables are based on the operation of a 100-kv. double-circuit steel-tower line 97 miles long during the period from March 1912 to October 1921.

The principal physical features of this transmission line are: Double-circuit steel towers 73 feet high, supporting two three-phase circuits of No. 1/0, six-strand copper wire; The three conductors of each circuit are on the same side of the tower, the vertical spacing between these conductors is nine feet; the horizontal spacing of the two circuits is 15 feet for the bottom and the top conductors, and 21 feet for the middle conductors; as originally built the horizontal spacing of the two circuits was the same for all three conductors but so much trouble was experienced with the wires whipping together when snow or sleet fell off the line, that in 1916 the spacing between the middle conductors was increased to 21 feet by putting a three-foot extension on each end of the middle crossarm. The average span length is 680 feet. The disk insulators used are of the cap and pin type manufactured in 1911, and these insulators are consequently a product of the early days of disk insulator manufacture. When the line was built, six of these disks were used on suspension assemblies and seven on tension or dead end assemblies. However, so much trouble was experienced with these insulators failing on tension assemblies that in 1915 all cap and pin disks used in tension assemblies were replaced with tension assemblies made up of eight Hewlett disks, and the number of cap and pin disks used in all suspension assemblies was increased from six to seven; this insulation is used at present, although as seen from Table III, the rate of failure of the cap and pin disks is rapidly increasing.

TABLE I

Failures located on test from 1912-1915 arranged according to location of disks in the assembly, disk No. 1 being adjacent to the conductor.

Disk No.	Top Wire	Middle Wire	Bottom Wire	Total
1	15	18	37	70
2	6	10	25	41
3	11	14	21	46
4	13	13	16	42
5	10	11	17	38
6	24	14	12	50
Total	79	80	128	287

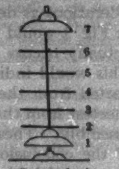


Cap and pin six-disk assembly

TABLE II

Failures located on test 1916-1921 arranged according to location of disk in the assembly, disk No. 1 being adjacent to the conductor.

Disk No.	Top Wire	Middle Wire	Bottom Wire	Total
1	112	112	100	324
2	101	96	90	287
3	193	204	135	532
4	246	203	147	596
5	237	210	181	628
6	259	211	186	656
7	281	239	212	732
Total	1429	1275	1051	3755



Cap and pin seven-disk assembly

Tables I, II and III refer only to the cap and pin disks used on suspension assemblies, there being on this line a total of 4452 such assemblies consisting of a total of 31,164 disks. The failures shown are only those located on our annual insulator test; failures causing cases of line trouble, which are invariably due to lightning, are not included as very often in such cases when three or four disks show signs of having been punctured the entire assembly is replaced. The information contained in Tables I and II is similar but it was necessary to separate it into two parts as the seventh disk added in 1915 was put in the position nearest the wire; the former No. 1 disc then becoming No. 2, No. 6 becoming No. 7 and so on. The small number of failures found in 1913, 1914 and 1915 is due somewhat to the fact that the tests made during these years were not as thorough as those that have been made in subsequent years.

TABLE III

Failures located on test from 1912-1920 arranged according to years and location of disks in the assembly, disk No. 1 being adjacent to the conductor. Total number cap and pin disks on suspension assemblies 31, 164, prior to 1916, 26, 712.

Disc No.	1913	1914	1915	1916	1917	1918	1919	1920	Total
1	14	26	30	54	51	41	42	36	294
2	8	22	11	21	20	44	22	69	217
3	8	22	16	20	48	63	40	124	341
4	9	23	10	26	44	85	60	127	384
5	5	14	19	30	55	88	67	116	394
6	3	23	24	21	52	88	40	160	411
7	..	..	..	43	71	103	42	170	429
Total	47	130	110	215	341	512	313	802	2470
% Total No. Disks	0.2	0.5	0.4	0.7	1.1	1.6	1.0	2.6	

Note: 1921 Figures not included in Table III.

From Tables I, II and III we find that the rate of failure for the position of the disk in the assembly instead of being greatest for No. 1 disk and then in the order Nos. 2, 3, 7, 4, 6, 5, which theoretical considerations as deduced from the voltage gradient curve in Fig. 1 would cause us to believe should be the case; actually occurs in the order Nos. 7, 6, 5, 4, 3, 1, 2. This would indicate that the longest life is to be expected from the disks nearest the conductor and the shortest from those at the tower or grounded end of the assembly. These results are exactly contradictory of the conclusions deduced by the writers of several recent articles based on their research work in connection with disk insulator assemblies.

Should further investigation and experience of operating companies show that the results embodied in Tables I, II and III are typical of the performance of disk insulators in service on high-voltage transmission lines over a period of a number of years, then it would appear that the present experimental efforts being made to distribute uniformly the leakage resistance among the disks of the assembly, by using shields grading the disks in the lower third of the assembly, or by other means, are misdirected energy and that the essential thing to be done is to devise some means which will increase the life of the disks in the top third of the assembly and particularly that of the disk attached to the tower.

As previously stated, the cap and pin disks on whose operating performance the figures given in the tables are based were manufactured in 1911, and are therefore, undoubtedly inferior to the disks manufactured today, since the porcelains now produced are superior to those of ten years ago. However, this has no bearing upon the relative rates of failure of the various units in the assembly; since the only requisite for a fair comparison of these rates is that the disks used in the assembly shall be of uniform quality, and as all of the disks were manufactured by the same concern at the same period this should be the case.

In closing it may be of interest to state that in 1915 this company reinsulated several of its transmission lines, replacing the cap and pin disks with Hewlett type disks; and that the cap and pin disks removed were used to add an additional disk on some of the other lines, among them being the line concerning which the data given in the tables included in this article were collected. From this it will be seen that the disks added on this line in 1915 were not new disks but ones which had seen previous service. Before being installed in their new position these disks were given a thorough test, the General Electric oscillator being used to make this test. Out of about 5000 disks so tested over 700 failed, and in 90 per cent of these the failure was found to result from the puncture of the porcelain inside of the cap, or just at the edge of the cap. In these disks the cap is cemented on and the pin into the porcelain with neat cement, and as the coefficients of expansion of the metal cap and pin, of the cement, and of the porcelain are all different, it is my opinion that the so called aging and ultimate failure of these disks is primarily, a mechanical failure due to the gradual crushing of the porcelain inside of the metal cap by the varying compressive stresses to which it is subjected, these resulting from sudden temperature changes such as occur when a heavy shower falls on a hot summer day. Our experience with these cap-and-pin type disk insulators is that they deteriorate just as fast in storage exposed to the weather as when they are in service on the transmission lines.

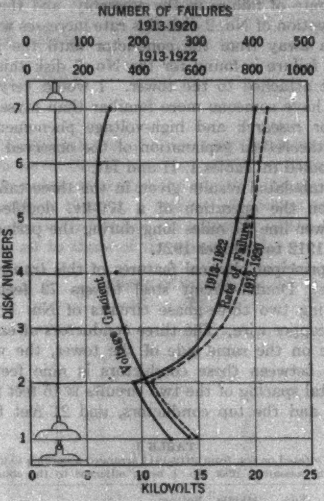


Fig. 1a—Revised to Include 1922 Tests.

Appendix

Table II revised to include 1922 test:
Test made June 1922

Disk No.	Top Wire	Middle Wire	Bottom Wire	Total
1	148	138	134	420
2	120	116	108	344
3	213	235	164	612
4	274	222	171	667
5	272	233	203	708
6	302	242	203	747
7	315	268	235	818
Total	1644	1454	1218	4316

Table III revised to include 1922 test: Test made June 1922

Disk No.	1913	1914	1915	1916	1917	1918	1919	1920	1921	1922	Total
1	14	26	30	54	51	41	42	36	100	96	490
2	8	22	11	21	20	44	22	69	111	57	385
3	8	22	16	20	48	63	40	124	237	80	658
4	9	23	10	26	44	85	60	127	254	71	709
5	5	14	19	30	55	88	67	116	272	80	746
6	3	23	24	21	52	88	40	160	295	91	797
7	...	...	...	43	71	103	42	170	303	86	818
Total	47	130	110	215	341	512	313	802	1572	561	4603
% Total No. Disks	0.2	0.5	0.4	0.7	1.1	1.6	1.0	2.6	5.1	1.8	

Discussion

R. J. C. Wood: There is a very interesting thing in Table 3. In the early years we find that the No. 1 disk is the one which is failing to the greater extent, in 1913, 1914, 1915, 1916; and then in 1917 No. 7, which is the one nearest the point of support, usurps first place and keeps approximately that position, so that on the whole in these latter years it is the one nearest the point of support which shows the greatest number of failures. Now we all know that in the years 1913, 1914, the kind of insulator we were getting was very different from the insulators we get today; and that raised the question in my mind as to whether those early failures may not have been due to one cause—perhaps soft, porous porcelain, which was to be had in plenty; and the failures of the later years, when it is to be presumed that most of that poor stuff had been weeded out, have been caused by prolonged mechanical vibration.

W. A. Hillebrand: Experience with insulators on this line has been extremely interesting. There are several points worthy of note. One is the extremely low rate of failure of insulators in the suspension position over a period of seven years. It is one of the very best that I know of, as you will see from Table 3, very much better than the records of many comparative insulators over the same period. The second is a comparatively high rate of failure of insulators in the dead-end position, so much so that I think after three years they were all removed in favor of another type.

Now, I think within a year after the construction of this line, it was subjected to a heavy sleet loading such that over one section there was about one conductor break per mile, with about twenty conductor breaks all told. This meant that the dead-end insulators were practically all over-stressed, which may have influenced their high rate of failure. This is particularly likely to be true, if as is my belief, many types of suspension insulators are operated under a false mechanical factor of safety, that is, the actual unit stresses are very often considerably higher than what is calculated.

In the matter of vibration there is one case at least on record of an insulator having been practically pulverized from this cause. In another case of a transposition tower, insulators, which were subjected to practically no weight whatsoever, were failing at such a rapid rate that it was necessary to add a very considerable weight simply to damp out the vibration stress.

The question has been raised as to the reason for the peculiar shape of the curve shown in Fig. 1, that is the higher rate of failure of the insulator next to the conductor than that of the one above. It is to be noted that this paper is probably a record of insulators removed from all causes, as a result of line testing and of actual failure in operation.

Porcelain is a heterogeneous, conglomerate material consisting of an aggregate and a binder. The mechanism of its failure is probably that of a slowly developing crack similar to the well known depreciation of tableware. As the bottom unit of a suspension insulator string has an operating potential considerably higher than that of any other unit it is conceivable that a deteriorating insulator would at last be weakened to the point where it would be punctured by the operating voltage. For an equal rate of depreciation this would occur more frequently in the case of the bottom units than with the others.

Porcelain is never completely annealed. Due to daily temperature changes it is subject to working stresses within the body of the material itself, independent of any which may be imposed by cemented hardware. These facts incline me to a belief in a gradual deterioration of the manner stated. Furthermore, so far as I am aware, there is nothing in all ceramic experience to indicate that a large percentage of insulators now being manufactured will not deteriorate at a slow rate.

E. E. F. Creighton: I want to take up that point that Mr. Wood asked, I think, and which bears directly on the subject, deterioration. In order to find out what was the matter I made two different kinds of tests; one I will mention at the present time.

Hundreds of insulators were punctured. After each one was punctured the process was to take some red dye and with the vacuum on the opposite side of the punctured hole send the dye through the hole, then set the insulator aside to dry. It took a day or so usually—if you want to have it done thoroughly. Then I take up the insulator and find what sort of puncture hole takes place.

We found from those tests that nearly all the punctures were due to folds or defects in the porcelain. As soon as you break it to pieces you will find that the dye has run in little flat streaks in there so that the porcelain actually opened up and there was a big flat place in there. If a porcelain punctures because of porosity you will find the puncture takes the shortest path through the porcelain, that is, if the porcelain is three-quarters of an inch thick it will go straight through the three-quarters of an inch. In general, however, the path of the discharge is very much longer than the thickness of the porcelain, showing that there was a definite defect.

The three ingredients, clay and feldspar and the flint in proportion, usually about five, three and two, are mixed with water in a large vat, and then it is necessary to get enough water out so as to get the clay in plastic form, that means going through a filter press, and the filter press takes out perhaps a little bit too much water. At any rate, these filter cases, about two inches thick, about two feet square are piled up one on top of the other and hammered down, and they are mixed as much as possible and hammered down in the pile and left for several days for the moisture to equalize, then they are put through a machine and thoroughly mixed up. Now during that process there are these little air pockets that may be in there, most of them to be sure eliminated or we would not have got good porcelain at all, but these little pockets do from time to time continue through all that process, and those are the little incidental conditions which make porcelain unreliable.

Now those of us who have worked with porcelain realize that a perfect piece of porcelain is an accident. It is a craft and it is only a question of how great those holes are.

Now, does porcelain deteriorate, is there any chance that we will ever get to a place where we can count on the porcelain for an indefinitely long time? In order to get some data on that subject I made up a large wheel that I have described elsewhere, called the Ferris wheel. It would not pass in here—it would turn in this room. On the outside of that wheel insulators were placed, standard insulators. At the bottom we used a special cooling means to get the temperature down to twenty degrees below zero, Fahrenheit. At the top we put in heating units and resisters so that we could raise the temperature any desired amount. In between we had a cooling space of air. With that apparatus we could change the temperature of the insulator over a range far greater than it would have in practise.

Now we put an insulator through that process, and assuming that twice around was equivalent to one year, we carried the insulators through dozens and dozens of years of life. The test was perhaps a little more severe than they would get in practise.

We have no very good way of determining whether there was deterioration there, but this much we can say that after they had passed through those many temperature changes, running it in and out continuously we could detect no deterioration of the porcelain. That gives hope that the porcelain does not deteriorate, in fact to the contrary, for the well-known methods of manufacture of porcelain it is my feeling that there is no deterioration of porcelain itself. The deterioration, as has well been pointed out by Mr. Wood, is mechanical.

Ivar Herlitz: In the years 1914 and 1915, a large number of suspension insulators were installed on the 70-kv. transmission lines operated by the Swedish Board of Waterfalls. The design of these insulators was preceded by considerable research work. An account of the principles brought out by this research work, and of the operating results with the insulators, was recently published in the Swedish technical literature (*Teknisk Tidskrift*, Jan. 1922). A brief summary of some aspects of this paper may be of interest in this connection.

The essential principles for the design of these insulators were as follows:

1. The porcelain was, as far as possible, relieved of tensile and shearing stresses; the possibilities for concentrations of the electrical field were reduced by avoiding all sharp corners.

2. Cap, pin, and porcelain were cemented together in such a way as to allow the metal to expand and contract freely in the axial direction under temperature variations; stresses on account of radial expansion of porcelain, cement, and metal were eliminated by means of elastic cushions between the various parts.

3. Certain experiments having indicated that electrical phenomena in the cement might have a detrimental effect, it was decided to short-circuit the cement by means of a conducting film on the porcelain, which film was connected to the cap and pin respectively.

More than 70,000 insulators of this design have been in operation for 7 years without showing any aging phenomena. Some 20 units have been exchanged, but only on account of damage from arcs.

Experience has indicated that the short-circuiting of the cement is of little importance, but the demand for this feature accidentally gave rise to an interesting experience. On the first insulators the conducting film was made of graphite, but on a later delivery, of which 8000 were put into operation, lead had been used. Of these insulators, 15 per cent failed in a few years. An investigation showed that this was entirely due to the fact that the lead became oxidized and thereby greatly expanded. This seems to furnish a strong argument for the importance of taking care of the stresses caused by expanding cement.

H. D. Panton: In reply to Mr. Wood I will say that we have never purchased any of the cap and pin disk insulators in question since 1911; replacements up to the present time having been made with disks removed from other lines when reinsulated with other disks. Disks so removed are tested with the G. E. oscillator, and those found good have been used for making replacements on the line under discussion in my paper. It is very probable that Mr. Wood's conjectures with regard to the cause of failure of No. 1 disks in the years 1913 to 1916 are correct; that such failures were due to defective porcelain. However, it must be borne in mind that the tests made in 1913-14-15 were not as thorough as those which have been made in subsequent years.

Referring to Mr. Hillebrand's remarks the average failure of suspension disks in ten years including 1922 has been only 1.5 per cent per year. With regard to the high rate of failure of insulators in dead-end assemblies, these were so high, that by the end of 1914, when the line had been in operation for a little over two years, it was necessary to decide on a replacement of all these insulators used in dead-end assemblies with insulators of another type.

The sleet storm referred to by Mr. Hillebrand occurred on April 1st-2nd, 1915, when this line had been in service for three years and we had already experienced so much trouble with these dead-end assemblies that we were preparing to replace them with Hewlett disks prior to the time when this sleet storm occurred. This storm caused the line to go down in over 40 places in a section forty-six miles long, practically all breaks being due to conductors breaking under the load of snow and ice; the snow and ice on the line was so heavy that a piece of No. 6 telephone wire measured in the storm area was found to be 9-in. in circumference, that is inclosed in an ice and snow sheath nearly three inches in diameter. Comparatively few insulators were found to be defective after this storm when a routine test of all insulators of this line was made. On suspension assemblies only 0.4 per cent of the disks were found defective. Figures are not available but I do not believe we found any large number of strain insulators which had failed due to the stresses put upon them by this storm.

With regard to Mr. Creighton's "ferris wheel test" I do not feel that two trips around his wheel produces stresses in the insulators equal to those experienced during a year of service on the transmission line. I consider the most severe stresses experienced by insulators in this section due to temperature changes, to be those produced when a cold shower falls on a hot summer day. The temperature of the porcelain in the sun is around 120 deg. Fahr. or higher and that of the rain in the neighborhood of 60 deg. Such an experience as this will happen to all of our insulators at least 25 or 30 times each summer. The top disk is most exposed to an experience of this kind and we have thought that this was possibly the cause why disks in this position failed with the greatest frequency. It is to be noted that the disks in discussion have no elastic cushion of any kind between the porcelain, the cement, and the metal. The cement being in direct contact with both the porcelain and the metal. Certain compressive stresses are obliged to be set up due to temperature changes; whether these stresses are of sufficient intensity to rupture the porcelain, I am not in a position to state.

Test and Investigations on Extra High-Tension Insulators

From a Purchasing Engineer's Point of View, with Special Reference to Methods of Test for Acceptance, Tests for Porosity and Deterioration.

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and

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Review of the Subject:—*Owing to repeated failures (the number of which increased as time went on) of 66,000-volt transmission line insulators (pin type) of the first Hydroelectric undertaking, carried out by the New Zealand Government, in 1914, and having in mind that Hydroelectrical Power was to be developed to the utmost of the Dominion's power resources—of which there are many—the investigations contained herein were commenced at the suggestion of Mr. E. Parry, B.Sc. M. I. E. E. late Chief Electrical Engineer to New Zealand Government, and has been continued for the past five years with the sanction and support of Mr. L. Birks, B. Sc. M. I. E. E. Chief Electrical Engineer to New Zealand Government, with a view to ascertaining the cause of such failures.*

It is the purpose of the paper to show

1. To what extent deterioration has set in on the 66,000-volt line referred to.

2. That the cause is due to the fact that the insulators were initially porous.

3. That tests at present in vogue with regard to ascertaining the porosity of insulator porcelain are totally inadequate, as the authors consider, immersion of the complete unbroken insulator under a pressure ranging from 1500 to 2000 lb. and the total amounting to 250,000 to 300,000 lb-hours the least that will give reliable results.

4. That non-porous insulators can be made that will remain good in service for an indefinite period and withstand perfectly the tests for porosity as recommended.

5. That individual testing with high frequency seems to be the only reliable method for testing for dielectric strength.

6. That a percentage test of each batch of insulators by the maker is unsatisfactory, because unless each shell of each insulator, in the case of pin insulators, and each disk in the case of suspension insulators, is definitely flashed over before being put to service, then breakdown trouble seems bound to ensue.

7. There is room for more cooperation between the insulator manufacturer and the purchasing engineer in regard to acceptance tests and the handling and maintaining of the insulator in service. If manufacturers will not agree to the tests as recommended by the authors, being made in the factory, then in countries such as this (New Zealand) which is situated so many thousands of miles from the point of manufacture, a public testing bureau should be established where undertakings could be arranged for, such tests to be made as described herein, when the cost of replacing the failures should be borne by the manufacturers.

8. That it has been found in New Zealand we have the necessary materials from which insulators can be and are being made, that will withstand the tests described equal to the imported wares.

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In this paper we propose to give an account of some investigations which we have carried out in conjunction with the Public Works Department of New Zealand, with a view to obtaining some definite information regarding the causes of insulator deterioration in connection with the Lake Coleridge electric power supply system. It is hoped that this may be of some service to those interested in the insulation of extra-high-tension transmission lines, which are to play such an important part in the hydroelectric development of this Dominion in the future.

It is the experience not only in New Zealand but in other undertakings abroad, that the problem of producing an insulator that will successfully withstand both electrical and mechanical stresses for an indefinite period, without deterioration or destruction, is one of the most difficult in connection with the transmission and distribution of electrical energy at extra high tension.

It is proposed to describe in detail the tests and the results of these tests, on several types and makes of insulators, including those of British, American (U. S. A. and Canadian), New Zealand, Australian, and German manufacture.

It is desirable to state briefly how the authors came to deal with such a variety of makes.

Considerable experience has been obtained with insulator failures on the Lake Coleridge electric power

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transmission line in this country, and at one time during the late war the position due to repeated failures became so acute that it was found necessary to purchase any makes available, having in mind that these investigations were about to be made. It was hoped that a careful investigation would demonstrate the best type and quality of insulator to withstand the requirements of the heavy duty called for, involving dielectric strength, mechanical strength and durability.

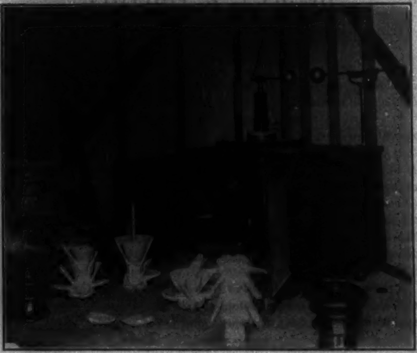

FIG. 1—SHOWING HIGH-FREQUENCY OSCILLATOR AND SAMPLES OF PUNCTURED INSULATORS

The apparatus employed consisted of:

(1) A 1000-volt 2000-megohm megger set.

(2) A 20-kv-a. 100,000-volt 50-cycle single-phase testing transformer with a double-scale 100,000-volt and 50,000-volt Kelvin electrostatic voltmeter.

(3) A General Electric Co. high-frequency oscillator set, capable of impressing 175,000 volts with spark gap for voltage measurements (See Fig. 1.).

(4) In the hydrostatic pressure tests for porosity, a steel testing vessel with cast iron ends capable of containing a complete insulator of the largest size, and of withstanding a pressure of 2500 lb. per sq. inch, with a high-pressure compressor capable of working up to this pressure (Fig. 2).

The electrical tests were carried out at the Public Works Department test room at Addington, Christchurch, and the porosity tests at the Physical Laboratory, Canterbury College, Christchurch. For the latter purpose the special high-pressure vessel mentioned above was provided from a research grant received from the New Zealand Institute, the assistance of which is hereby acknowledged.

A detailed account of the vessel may be given, as it was eminently successful. After pumping up to a pressure of, say, 2200 lb. per square inch, it would frequently retain the pressure so well that it had not fallen below 1500 lb. per sq. inch in four days, although no further pumping had been done in the meantime.

A hollow piece of cast steel 15 inches in internal diameter, 19 inches in external diameter and 20 inches long, was turned at both ends, and a narrow spigot was left about ¼ inch from the inner edge and running round each end. This spigot was 3/8 inch high and about 3/16 inch wide. The spigot fitted with a corresponding groove in the covers which was ½ inch deep. The groove and spigot were of such a width that a piece of leather sewing machine belting fitted the groove exactly in width. When the end pieces were screwed down, the spigot was seated upon the leather belting and made a satisfactory joint. The end pieces or covers were of good cast iron eight inches thick, and held on by 12 bolts each 2 inches diameter. When the pressure was first applied at about 800 lb. per sq. inch, it was seen that moisture was "weeping" through the bottom cover, but this righted itself probably by internal corrosion and no further trouble was experienced.

An illustration of this testing vessel is shown in Fig. 2.

Under this test the amount of penetration is apparently proportional both to the hydrostatic pressure attained, measured in lb. per sq. inch and to the time of immersion. The authors, therefore, propose to measure the intensity of the test by the product of these two factors or by the "pound-hours" to which a square inch of the insulator has been subjected.

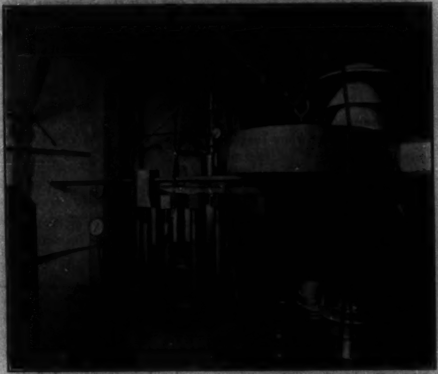

FIG. 2—SHOWING LARGE POROSITY VESSEL USED FOR THE TESTS DESCRIBED HEREIN, ALSO THE SMALL VESSEL IN RIGHT CORNER USED FOR THE EARLIER TESTS

The usual test adopted was at a pressure of 1500 to 2000 lb. per sq. inch applied for a period of seven days, *i. e.* for 250,000 to 300,000 pound-hours. We wish to insist strongly that the intensity of the porosity test to be of any value should be of this order. One important firm claims credit for its insulators because they will withstand a porosity test at a pressure of 200 lb. for 24 hours—*i. e.* 4800 pound-hours! In view of the prolonged exposure to the weather to which the insulators are subjected in service, although only at atmospheric pressure, we consider that such a test is totally inadequate, in fact that any porosity test of less than 200,000 pound-hours is comparatively useless.

With regard to the efficiency of testing with high-frequency oscillations as compared with low or working frequency, the former gives, in the authors' opinion, much the more searching and reliable results.

After the Lake Coleridge 66,000-volt transmission line had been in service about two years, the insulator failures became so frequent that it was decided to test each insulator of the remaining stock of 500 individually, so as to insure that those used to replace the failures were reliable and good, and for this purpose the high-frequency oscillator was used.

The original consignment of insulators was imported in 1913 and this stock of 500 replace insulators was obtained in 1915 and stored in the open. They had of course withstood the makers' factory tests, but on being retested two years after delivery, during which they had been exposed to the weather in the works yard, no less than 43 or 8.5 per cent were found by individual tests to be defective. In several cases these insulators were of porous material, and had absorbed moisture during the period they had been in stock, as was proved subsequently.

Each of these replace insulators as it was tested, was numbered and its position on the lines when put into service was recorded, and although over five years have elapsed since these precautions were commenced, and over 200 breakdowns due to insulator failures have occurred, and over 500 insulators have been replaced, not one of the tested insulators has yet given trouble, which shows the efficacy of the method of testing individual insulators after they have been exposed to the weather in stock for a couple of years, thus weeding out porous ones. The main cause of deterioration of the insulators that did fail was apparently absorption of moisture, and if porous insulators are detected and excluded, insulator deterioration will largely diminish.

It seems to be the practise of some makers to test insulators with a set pressure at working frequency, from head to pin, and from these results to pass the batch or otherwise. We consider that this method is unsatisfactory, inasmuch as the faulty shells will not betray themselves (being protected by the good ones) unless each shell is individually flashed.

Further, this flashing should be done by high-frequency pressure, for the authors' experience has been that, where insulators have been guaranteed by the makers, as tested at a certain pressure, at low or working frequency, they have failed decisively when tested with the high-frequency oscillator at many thousands of volts below the guarantee. Others have withstood the pressures named by the makers *from head to pin* on both high and low frequency; but on individual testing of the shells, some were apparently mechanically perfect, but electrically were almost conductors, as will be seen later in the description of tests.

METHODS OF TEST

The following program of tests was adopted:

(1) Measure insulation resistance of each shell with 1000 volt megger;

(2) Subject each shell separately to bare flash-over pressure at 50 cycles (working frequency) for 15 seconds;

(3) Subject each shell separately to bare flash-over pressure at high frequency for 15 seconds (Fig. 1);

(4) The complete unbroken insulator was placed in the porosity testing vessel and covered with a strong aqueous solution of fuchsin (Fig. 2). A hydrostatic pressure of 2000 lb. per sq. inch was then put on the vessel, and the insulator remained immersed in the fuchsin solution under a pressure ranging from 1500 to 2000 lb. per square inch for about a week, that is, until the number of pound-hours had reached 250,000 or 300,000.

As soon as convenient after removal from the porosity vessel the electrical tests were repeated, after which the insulator was broken up for signs of penetration. If the samples submitted withstood this complete set of tests without breakdown or signs of penetration, the batch was considered satisfactory.

It is worthy of note that of twelve makes tested, samples of seven failed to pass the tests, which shows the necessity for special acceptance tests in all cases.

It was impossible with the apparatus at our disposal to subject more than a very few individual insulators of any make to the hydrostatic pressure test for porosity. Some of the insulators so tested have been chosen to ascertain the cause of certain weaknesses previously known to exist; and the weaknesses have generally been found to be due to, or at least associated with, a band of porous material in the body of the porcelain. We consider, therefore, that if any of the few insulators in any batch that may be submitted for test are found to be porous, the whole of the batch should be rejected, and the maker informed that a repetition of such an experience would seriously jeopardize his chance of securing future contracts.

MEGGER TESTS

While the megger test has its limitations, yet it seems to be advantageous in connection with the hydrostatic pressure tests; in that, after the insulator has been under the hydrostatic pressure, it is possible to obtain with the megger definite indication of the condition of the shells; but the greatest care must be taken when testing with the megger, for not only the humidity of the atmosphere, but even the handling of the insulator or the megger leads, will often tend to lead to wrong conclusions.

When testing insulators with the megger—dry as received—it has been noted with a dry contact, however thorough, that results are by no means consistent, as it is almost impossible to "wipe" the whole of the surface of the joints between shells with the contact lead, and if any portion is missed, a puncture path or porous spot may also have been missed owing to the high resistance of dry cement.

It has therefore been found essential to cover the cement joints to a depth of about 1/16th of an inch with weak acid, which gives a sure contact over the whole area of the cemented joint, and more consistent results are obtained. But if high-frequency tests are to follow, the results of the high-frequency tests are likely to be misleading, unless the joints are thoroughly cleaned, because the oscillator cannot supply the C^2R losses due to dampness without undue voltage drop and probably the voltage would not reach flash-over owing to the poor regulation of the oscillator.

Humidity of the air, and human handling, are important factors when testing insulators with the megger, and it is therefore only on the driest of sunny days that megger tests should be attempted.

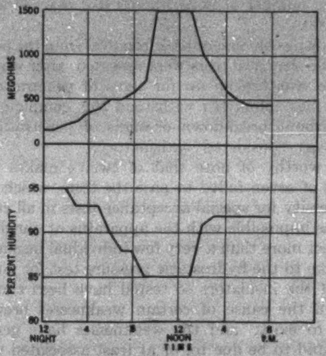

FIG. 3—INSULATION AND HUMIDITY CURVES—66,000-VOLT PIN INSULATOR

The curves in Fig. 3 give the results of megger tests on an insulator over a period of 20 hours during a day in early spring, and show that, in this latitude, it would not be reliable to test insulators with a megger outside the hours of 10 a. m. and 2 p. m. during certain seasons, or that megger tests should not be conducted when the percentage of humidity is much over 85.

It would seem therefore, that where, owing to porosity, the insulator may be a partial conductor, as for instance an old insulator which has been in service some years, and with no other means of test at hand, the megger may be used to advantage, but with recently made insulators, being tested for acceptance, the megger test could be dispensed with. Factory inspection has reached a stage in which faulty insulators, that could so easily be detected, would surely never leave the factory.

HIGH-TENSION TESTS AT WORKING FREQUENCY

When no other means are available, this method—provided each shell is separately tested to flash-over—is useful.

This can be arranged where working pressure is available, and, provided each shell is tested separately at working pressure, the aggregate flash-over of the whole insulator may be assessed.

To subject an insulator to working pressure, applied from head to pin, as an acceptance test is misleading, and the results are of practically no value. It will find those which are defective in all shells—a state of affairs hardly to be expected with the present-day makes of insulators—but it will not betray any single shells that are faulty; and if there are any such, the seeds of trouble for the transmission line are sown.

A section of three miles of the Lake Coleridge transmission lines runs in duplicate alongside a steam railroad. After two years' service, 12 insulators were taken down at random for testing purposes. In every one of these 12 insulators the inner shell of the four was completely coated with a black deposit, and a test showed the shells so covered to be conductors, and hence it can be reasonably assumed that the factor of safety of all insulators near the railroad was reduced by 25 per cent, due to this deposit. With mechanical troubles developing on the top shell, due to cable loading, cable clamps, etc., the factor of safety is still further reduced, and if there happen to be one or two bad shells coupled with a mild surge due to switching or dropping of load, the insulator will break down so much earlier.

It is noteworthy that 47 or 19.8 per cent of the number (264) along the line of railroad have failed or had to be replaced during six years. A few of the breakages were mechanical but it is most probable some of the shells were "electrically down" before being put on the line.

On one occasion, about one-half mile from the railroad section, a single inner or fourth shell insulated the line for eight hours, the other three having punctured decisively.[1] This certainly could not have taken place on the railroad section, where each fourth shell was coated as described.

It therefore appears that it is absolutely essential that all shells must be tested individually.

TESTS WITH HIGH-FREQUENCY OSCILLATOR
(Prof. E. E. F. Creighton's Method)

Where this apparatus is available, it has been found to be more effective in detecting faulty insulators, provided they are dry and non-porous, but as stated previously, to test from head to pin, by running up to the full capacity of the oscillator set, is very misleading, although if two or more shells are "down" (which is hardly likely with the modern makes of insulators), then indications will be quite clear.

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[1] Birks & Ferguson, N. Z. *Journal of Science*, Vol. 3, No. 4, page 184.

If a 300,000-volt set is available, then head to pin tests could be resorted to in order to save time, but it would still be very necessary to note that each shell must definitely flashover.

With the present-day makes of insulators, where perfect vitrification is aimed at, the megger and low or working frequency tests could be safely discarded in favor of testing individual shells by high frequency, combined with a percentage subjected to the hydrostatic pressure tests for porosity, for it has been found that where other methods have proved doubtful and some even shown the insulator to be apparently sound, the high-frequency pressure has shown them to be "down" at a comparatively low voltage.

Some engineers are doubtful as to the advisability of subjecting insulators to "flashover" on high frequency before being put to service, fearing undue stress resulting in possible damage.

Local experience tends to show that insulators so tested are quite undamaged, for upwards of 1000 insulators have been so tested (*i. e.* each shell up to flash-over on high frequency for 15 seconds) and as previously stated, over 500 have been put on the lines referred to and, although nearly five years have elapsed since the first replacement was made and over 200 breakdowns have occurred, not one of those so tested has yet failed electrically. One had to be replaced owing to damage due to rifle fire, but although mechanically damaged it was electrically as good as the day it was placed in service.

The authors have a special insulator, which has been used for hundreds of demonstrations of Creighton's Super Spark Potential Test[2]; and a certain suspension insulator which supports the high-tension lead of the high-frequency oscillator, receives full punishment every time the set is used, yet both these insulators are apparently quite undamaged. Such authorities as Creighton,[3] "consider that such tests are quite mild, and correspond to a rare case of switching and further are nothing more than the insulator may get in operation in due time;" and Peaslee,[4] states, "accumulated evidence of a large number of tests, covering combined electrical and mechanical tests, fatigue tests, and high-frequency tests, indicates such stressing has no effect whatever upon the properties of the insulators."

Many suggest, for safety, taking each shell up to bare working pressure only, but the authors have found in seven instances at least a pin hole or other fracture at or about 1 in. from the edge of the shell which it did not betray itself at bare working pressure, but at approach of flashover, the arc concentrated at the point of fracture, and in less than one minute the shell cracked. These would have been passed on a bare working pressure test.

The authors are therefore of opinion that it is absolutely essential to see that each shell should withstand flashover pressure at high frequency for at least 15 seconds continuously.

DETERIORATION

On the Lake Coleridge transmission lines there are over 5000 insulators and over 800 or 16 per cent have had to be replaced in six years, either owing to failure in service, or to patrolmen's observations of mechanical defects, and our experience indicates that this is due mainly to initially porous insulators, coupled with mechanical weakness.

We have found from experiment and experience that porcelain can be made which is nonporous to the limit of the somewhat severe tests we have applied, and in that case, moisture will not get into it, whether the insulator be in service or otherwise.

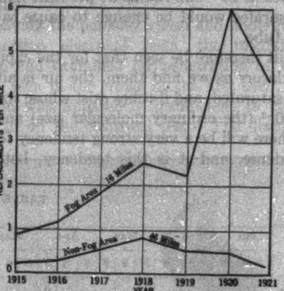

FIG. 4—CURVES SHOWING INSULATORS REPLACED ON TRANSMISSION LINES

Curves are shown in Fig. 4 giving the numbers that have failed in a fog or mist area, and we consider that there is no doubt that the cause is due to porous insulators, absorbing moisture to such an extent as to render some shells practically conductors, when attacked by high-frequency surges or even at working pressure.

No doubt many other bad insulators are on the lines in other areas, where fog or mist is not prevalent, and in course of time these will be weeded out by breaking in service.

The diameter of the capillary tubes in even the most porous insulators we have tested is extremely small. In the first experiment we used fuchsin as the coloring agent, by which the penetration could be traced. Finding however, some difficulty in photographing the color, though it was strongly visible, we discarded it for the time being for red ink, or rather a solution of red ink powder in water. It was noticed, however, that it seemed extremely difficult to force the red ink into the porcelain. A faint coloration was frequently noticed, but not such as might have been expected from the red ink. It seems likely that the size of the capillaries was less than 10^{-6} cm. in diameter. It must be remembered that both capillary "suction" and the tendency of moisture to condense in a capillary tube, increase as the diameter of the tube decreases. In the case of capillary "suction," the effect is inversely proportional to the diameter. In the case of condensation the ratio of the saturation vapor pressure on a plane surface and in a capillary tube is given by the expression

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[2] Creighton, Insulator Testing, A. I. E. E. JOURNAL, May 1915, page 765.

[3] Creighton, Insulator Testing, A. I. E. E. JOURNAL, May 1915, page 766.

[4] Peaslee, W. D. A., Insulator Porc., A. I. E. E. JOURNAL, Vol. XXXIX No. 5, page 445.

$$\log_{10} \frac{\omega}{\omega'} = \frac{5.6 \times 10^{-8}}{r}$$

where ω is the saturation vapor pressure for the plane surface and ω' that for the capillary.

Taking this latter effect, it is well-known that for capillary tubes, where the radius is 10^{-5} cm. the saturation and vapor pressure on a plane and in such a capillary are very approximately the same, whereas for tubes of 10^{-7} cm. radius 30 per cent humidity on a plane surafce would be enough to cause saturation of such a tube.

It will therefore be seen that for the capillary tubes in insulators as we find them, the air is always practically saturated, and if tubes exist whose size is greater than 10^{-8} (the ordinary molecular size) and less than 10^{-6}, there will be a very strong tendency for moisture to condense, and it is this tendency, both owing to capillary "suction" and to condensation, which we consider has been the cause of the deterioration that has been experienced.

It cannot be too strongly emphasized that a porous insulator is certain sooner or later to give trouble. The pores of such an insulator consist of extremely fine capillary tubes, and the whole tendency of moisture, is to condense in such tubes, which never, even on the warmest day, a corresponding tendency for the moisture to evaporate. Thus the moisture is always increasing in quantity within the body of the insulator until a time comes when the insulator is electrically so much weakened by the accumulated moisture, that it punctures and serious trouble results. The authors consider that no laboratory test for porosity, however severe, can be as drastic as prolonged exposure to the atmospheric conditions in all weathers. Any batch of insulators showing porosity should be rejected unhesitatingly, or trouble is certain in the long run.

The observations made in the fog area referred to are interesting. The area extends from Christchurch, westward for a distance of 16 miles, and is no doubt due to the prevalent easterly winds blowing in from the sea, carrying westward the smoke particles of Christchurch, and moisture laden air from the sea. It is on these smoke particles that the moisture condenses and forms the mist in the region referred to. Further out than 16 miles the effect is not so perceptible. See Fig. 4.

TABLE I.—INSULATOR REPLACEMENTS

Per Area—Per Month

Year		Jan.			Feb.			Mar.			Apr.			May			June			July			Aug.			Sept.			Oct.			Nov.			Dec.			Total per area		Total per year
		N	S	F	N	S	F	N	S	F	N	S	F	N	S	F	N	S	F	N	S	F	N	S	F	N	S	F	N	S	F	N	S	F	N	S	F			
1915	Fog	..	..	..	..	..	..	..	..	..	..	..	0	..	2	2	1	1	2	..	..	0	..	..	0	..	1	1	..	1	1	3	..	3	3	2	5	Fog	14	26
	Non Fog	..	..	..	..	..	..	..	..	..	3	..	3	..	1	1	1	1	2	..	..	0	..	..	0	..	3	3	1	1	2	..	..	0	1	..	1	Non Fog	12	
1916	Fog	1	4	5	4	..	4	..	..	0	2	..	2	..	..	0	..	..	0	3	1	4	..	..	0	..	..	0	..	..	0	..	..	0	3	1	4	Fog	19	33
	Non Fog	2	5	7	..	..	0	..	..	0	2	..	2	..	..	0	..	..	0	..	..	0	1	..	1	..	..	0	..	..	0	..	..	0	..	4	4	Non Fog	14	
1917	Fog	1	..	1	1	11	12	..	1	1	1	1	2	3	1	4	1	..	1	..	..	0	..	2	2	2	..	2	..	3	3	..	..	0	..	2	2	Fog	30	57
	Non Fog	1	..	1	2	1	3	..	1	1	2	1	3	2	5	7	1	2	3	..	..	0	1	1	2	3	..	3	..	3	3	..	..	0	..	1	1	Non Fog	27	
1918	Fog	1	..	1	..	4	4	2	..	2	..	..	0	2	2	4	..	2	2	3	4	7	2	1	3	2	..	2	5	1	6	2	2	4	..	5	5	Fog	40	78
	Non Fog	1	..	1	..	3	3	..	..	0	..	..	0	1	1	2	..	2	2	2	5	7	..	2	2	2	..	2	6	3	9	3	2	5	..	5	5	Non Fog	38	
1919	Fog	..	..	0	6	..	6	..	4	4	..	..	0	..	2	2	6	..	6	1	4	5	2	..	2	2	2	4	..	3	3	..	..	0	2	2	4	Fog	36	62
	Non Fog	1	..	1	4	..	4	..	2	2	..	..	0	..	..	0	..	..	0	1	3	4	..	2	2	1	2	3	2	..	2	5	..	5	..	3	3	Non Fog	26	
1920	Fog	1	..	1	3	13	16	10	3	13	..	1	1	8	1	9	17	6	23	..	..	0	..	..	0	..	7	7	..	..	0	6	..	6	4	16	20	Fog	96	121
	Non Fog	1	..	1	..	2	2	2	..	2	..	3	3	..	..	0	7	..	7	..	..	0	..	..	0	..	2	2	..	..	0	1	..	1	1	6	7	Non Fog	25	
1921	Fog	2	6	8	14	3	17	2	..	2	..	..	0	4	3	7	..	..	0	8	5	13	3	3	6	7	..	7	8	..	3	..	4	4	..	..	..	Fog		
	Non Fog	1	1	2	1	..	1	1	..	1	..	..	0	..	..	0	..	..	0	2	1	3	..	1	1	..	..	0	..	..	0	..	..	0	..	..	..	Non Fog		

Fog Area 16 miles. Non-Fog Area 46 miles.

The two 66,000-volt transmission lines referred to were erected in 1914 and have been in continuous service since 1915, and Table I shows the number of pin insulators which have failed in the consecutive years of service.

This table is plotted in Fig. 4, and Fig. 5 shows the total replacements.

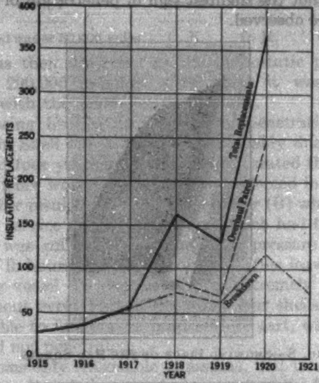

Fig. 5—Curves Showing Insulator Replacements

In addition to these, 72 suspension disks (12 strings of 6 each) used at anchor towers, were replaced as a result of the complete failing of two strings (12 disks).

Dealing first with the pin type, it will be seen for the year 1919-1920 that over 360 were replaced due to all causes and 100 of these were selected at random and tested on the high-frequency oscillator.

58 were found to be "down" on 2 or more shells.

42 were found damaged on top shell only. It will therefore be seen that not even one per cent was electrically whole.

36 of the suspension type were tested and 22 or 60 per cent were found to be "down" and a test under hydrostatic pressure showed the porcelain to be of a porous nature.

Tests and Results—Pin-Type Insulators

The following is a summary of the average results of many tests on insulators by various makers.

Tables of Dry Flash-over Pressures in Kilovolts (high frequency)
4-Shell and 3-Shell Pin Type

Maker	Shell No. 1	Shell No. 2	Shell No. 3	Shell No. 4
A.	74 Kv.	55 Kv.	66 Kv.	75 Kv.
B.	66 "	65 "	76 "	60 "
C.	70 "	50 "	66 "	64 "
D.	76 "	68 "	92 "	
E.	72 "	74 "	66 "	
A.1	82 "	56 "	70 "	
A.2	64 "	64 "	80 "	
F.	64 "	67 "	66 "	
E.1	58 "	74 "	58 "	
E.2	60 "	50 "	64 "	
E.3	45 "	33 "	45 "	
G.	65 "	55 "	..	

Maker A—66,000-Volt 4-Shell Pin Type. This insulator which had not been in service, was, after testing all right on each shell at both high and low frequency, subjected to hydrostatic pressure test of 246,000 lb-hr. with an average of 1440 lb. per sq. in.

After immersion, a repetition of the electrical tests showed the insulator to be as good electrically as it was before immersion, and when broken up, not the slightest sign of penetration could be seen.

Maker B—66,000-Volt 4-Shell Pin Type. This insulator had been in service since 1914, but had been removed 5 years later owing to having shown signs of puncture on one shell on overhaul.

Electrical test showed the shells to be in the following condition:

	Shell 1	Shell 2	Shell 3	Shell 4
Before Immersion.	O. K.	O. K.	Punctured	O. K.
After Immersion...	O. K.	Conducting	Punctured	O. K.

It will be noted that No. 2 shell failed under the hydrostatic pressure test, which consisted of 280,000 pound-hours.

After leaving the porosity vessel and undergoing the after-immersion electrical tests, the insulator was broken up and examined for penetration of the dye. Color was seen in the crown of the first shell, but the penetration was apparently insufficient to cause the shell to fail on the electrical test. The discoloration of the second shell was most marked. It would seem as if the dye had found its way into the shell through the glazing, and as seen above, the tests showed the shell to be practically a conductor after the porosity test.

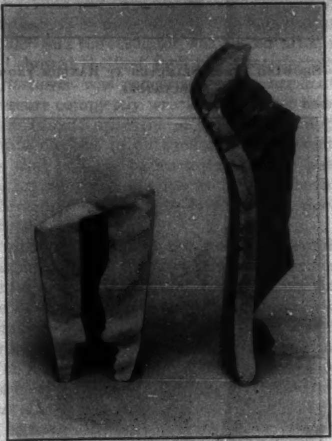

Fig. 6—Showing on Right Penetration in Second Shell, and on Left, Good Porcelain which has been Subjected to Same Tests

In the third shell, the only sign of penetration was found just around the small hole in the shell where puncture had taken place prior to immersion and was evidently the cause of the puncture.

In the fourth shell, the porcelain was white and satisfactory throughout. It seems reasonable to assume this insulator was sound as far as the factory tests could reveal when first put on the line, but had gradually deteriorated, owing to the material being initially porous. Fig. 6 shows the penetration in a section of shell No. 2 mentioned above.

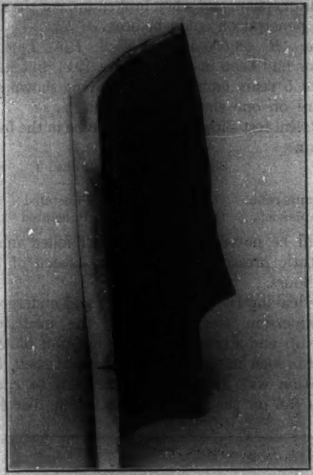

FIG. 7—SHOWING PIECE SELECTED AT RANDOM FROM WHOLE INSULATORS

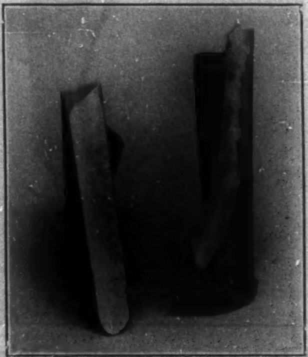

FIG. 7A

Another insulator of the same type, by the same maker, had been on the line a year longer than the previous one, and was removed owing to a mechanical fracture having been observed, probably due to rifle fire or other external cause. Pieces of this insulator were subjected to a hydrostatic pressure of 280,000 lb-hours, after which, when broken into very small pieces, not the slightest sign of penetration of the dye could be observed.

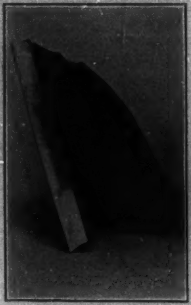

FIG. 8—SHOWING PIECE OF THE BAD SHELLS

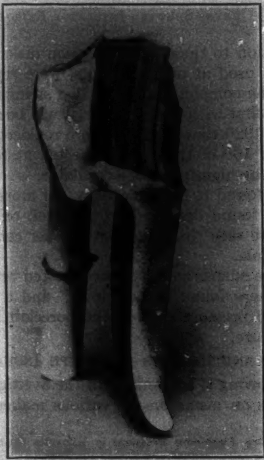

FIG. 8A—SHOWING PIECE OF THE TOP SHELL

It is therefore reasonable to assume, that apart from the mechanical fracture, the insulator was electrically as good as when first put on the line and would have remained so indefinitely, had it not been replaced.

Another insulator of the same type and maker (B) was immersed in water at atmospheric pressure for four years.

The electrical tests made in 1917 before immersion, showed the insulator to be good after flashover for one minute on each shell, at both high and low frequency.

After leaving the tub, in 1921, the insulator was wiped and allowed to dry for one hour in the ordinary atmosphere after which it was, where possible, taken up to flashover on high frequency, with the following results:

Shell 1	Shell 2	Shell 3	Shell 4
Punctured under 50,000 volts.	O. K.	O. K.	O. K.

It was then subjected to the hydrostatic pressure test of 290,000 lb-hours, after which it was again tested, with the same electrical results.

On being broken up, no sign of penetration was visible in Shell No. 1. This was probably due to the fact that four years immersion had saturated the shell, and no more water (colored) could be forced in.

Another insulator, by the same maker (B) which had been in service over six years and which had failed in service was subjected to hydrostatic pressure test of 280,000 lb-hours and when broken up after leaving the porosity vessel the penetration was extremely marked throughout every part of the whole four shells, it was impossible to find even a most minute part, where the dye had not penetrated.

It seems only reasonable to assume, that this insulator let the line down; not due to surge or the like, but simply that it had become impregnated with moisture, through being porous, and had therefore eventually become practically a conductor for extra-high-tension pressure (Figs. 7 and 7A).

Still another 66,000-volt pin-type insulator by Maker B, which had been in service for six years, and failed from no apparent cause, was subjected to the hydrostatic pressure test of 280,000 lb-hours and when taken out of the porosity vessel and broken up, it was found that whereas two of the shells were the same as the last mentioned, *i. e.*, penetrated right through, the other 2 shells were of quite good material.

There seems no doubt that this breakdown was caused by the power arc tending to flash over the insulator, that the two shells were practically conductors, and therefore ruptured by being in the direct path of the arc, thus causing the complete wreck of the other shells.

The individual testing of each shell as urged in this paper, would have obviated this trouble. (Figs. 8 and 8A.)

Maker C—66,000-Volt 4-Shell Pin Type withstood all electrical tests and showed no sign of penetration after having been through the hydrostatic pressure test.

Maker E—66,000-Volt 4-Shell Pin Type. A firm which specializes in the manufacture of E. H. T. insulators, sent a special sample insulator which was expected to withstand any electrical tests applied, having withstood all the maker's tests.

Each shell was tested separately up to flashover on 50 cycle pressure, which each shell withstood.

Each shell was then tested on the high-frequency oscillator, shells 1 and 2 withstood flashover satisfactorily, but No. 3 punctured decisively in the thickest part, under 40,000 volts.

The puncture path was quite perceptible when the shell was broken up, and had the appearance of a seam of flint, which apparently had not been "found" by the low frequency test.

If such results are obtained with a specially selected sample, what risk has an undertaking in accepting many thousands which have been passed by the maker, due to perhaps less than 10 per cent of their number having passed a mild low-frequency test?

In fairness to the maker, it should be mentioned that all his tests were made on 25-cycle pressure and the whole insulator, after being subjected to the hydrostatic pressure test, showed absolutely no signs of penetration.

Maker F. Another case of a world-known porcelain firm but not insulator makers, who desired to enter the electrical field, submitted a three-shell 66,000-volt pin type insulator for test. This insulator was guaranteed tested, by certified authorities, to 125,000 volts head to pin.

Each shell was taken up to flashover on 50-cycle pressure, which it withstood for two or three seconds, but on the high-frequency pressure, one shell only stood up to flashover, while the remaining two failed decisively under 30,000 and 40,000 respectively.

The insulator was then subjected to the hydrostatic pressure test. The number of pound-hours submersion was 300,000 and the insulator was tested after immersion and showed the first shell to be satisfactory in so far as flashover was concerned. The application of high pressure completely wrecked the other two shells, and when broken up, signs of penetration of the dye were quite obvious in all shells. It is reasonable to assume, that had the hydrostatic pressure been kept on for a longer period the dye would have been forced right through, sufficiently to form a path electrically through the first shell.

This again demonstrates the necessity for individual shell testing, because this insulator had been tested by authorities as good for 125,000 volts. This was true, because even after the insulator had been under the hydrostatic pressure test, it would withstand 120,000 volts from head to pin. But should such an insulator be put on a line? And yet how many, in such a condition are unwittingly put on a line?

Maker D. A particularly good insulator by this maker, although it has only three shells, has nearly as high flashover as some of the four-shell type.

It withstood all electrical tests satisfactorily and was then subjected to the hydrostatic pressure test, after which it also withstood the repetition electrical tests. It was further given Creighton's super-spark potential tests on each shell for five minutes, and withstood this test. On breaking up, not the slightest sign of penetration could be seen; and if the maker could only guarantee consistency, this insulator, by virtue of its shape (Fig. 13) and quality of material, should make many friends, but as seen from the foregoing tests, purchasing engineers have reason to be suspicious, unless some guarantee is given that each and every shell of each insulator has been subjected to such tests as those described.

TESTS AND RESULTS 66,000-VOLT SUSPENSION INSULATORS

66,000-Volt Suspension Type	
Maker	Flash-Over kv.
H.	110.
H.1	98.
B.1	88.
B.2	80.
A.3	80. Approx.

In addition to the several types of pin insulators tested, three makes and five samples of different shapes of suspension insulators were included in the investigations, and the results have been that three samples or 60 per cent failed to withstand the prescribed tests satisfactorily; the two that did withstand the tests coming from one Maker H who has undoubtedly specialized in this type and succeeded in attaining something unassailable in his product.

The flashover pressures are given below, and it will be noted that apparently makers have opposite aims; Maker H having, in his latest product, increased his leakage distance, while Maker B in his latest product, has decreased his leakage distances as shown:

Maker	H.	received	in 1917	has	flashover	of	98,000	volts
"	H.	"	" 1921	"	"	"	110,000	"
"	B.1	"	" 1914	"	"	"	88,000	"
"	B.2	"	" 1921	"	"	"	80,000	"

The product of Maker H has successfully withstood all tests, while that of Maker B has failed badly in both samples.

Maker A, who has a reputation for pin insulators, equal to the best known, had failed up to that time in his attempt to produce a suspension insulator. There is an inherent weakness in the design, in that the insulator punctures much below flashover pressure, also the porcelain was found to be unmistakably porous, illustrating the fact that even the best of porcelain makers are inconsistent in their products in the case of new types or shapes.

Maker B. (*1*). This supension insulator supplied in 1913 had been in service over six years, being one of a string of six which failed completely in service, from no apparent cause, just prior to the day load coming on. It was subjected to the hydrostatic pressure test, and on breaking up, after leaving the porosity vessel, it was found that the dye had penetrated to a considerable depth. (Figs. 9 and 9A.) From the above it can be reasonably assumed that the failure of this and the rest of the string of disks from which it came, was due to deterioration caused by the material being initially porous and moisture had gradually accumulated, until the material lost its insulating properties.

Maker B. (*2*). This was a new type supplied recently by the same maker who was seeking to redeem his reputation, which was seriously jeopardized, by results obtained from his earlier insulators. The sample withstood all electrical tests, both before and after having been subjected to the hydrostatic pressure test, and when broken up, no signs of penetration of the dye were observed, but a second sample, when tested dry, punctured decisively at 75,000 volts at 50 cycles.

The two pieces of the broken second sample were subjected to the hydrostatic pressure test, and on breaking up after leaving the porosity vessel, it was found that the dye had penetrated deeply at the weakest and most critical point of the insulator. This was regrettable with such a recent production (1921), but certainly goes to confirm the author's contention regarding individual tests (Figs. 10 and 10A.)

FIG. 9—PIECE OF SUSPENSION INSULATOR SHOWING MARKED PENETRATION. MAKER B'S EARLY PRODUCT

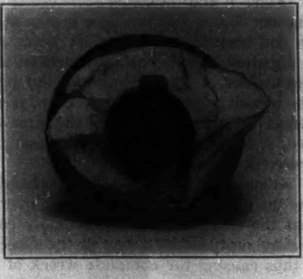

FIG. 9A

Maker A. (*3*). *66,000-Volt Strain Insulator.* This insulator apparently has an inherent weakness in its design, inasmuch as several samples, punctured decisively under 60,000 volts (flashover should be about 80,000 volts).

One of the unbroken samples was subjected to the hydrostatic pressure test, and when broken up, after leaving the porosity vessel, it was found that the dye had penetrated throughout the whole thickness, in fact, this was amongst the worst material handled in these investigations, although as before stated, this maker's material in the pin type productions, is unassailable and equal to the best handled by the authors.

Maker H. 66,000-Volt Suspension Insulator. This maker claims to have produced a porcelain that is unassailable in that it is perfectly vitrified and will withstand any electrical, mechanical or porosity tests. The insulator was subjected rigidly to the whole of the tests mentioned herein, and after the porosity tests, was further given Creighton's super-spark potential tests for five minutes. On breaking up, after having successfully stood all tests, not the slightest sign of penetration of the dye could be seen.

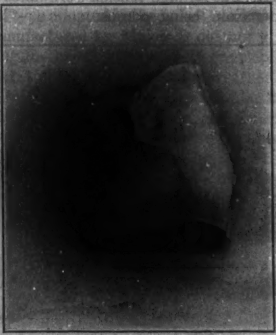

Fig. 10—Showing Maker B's Later Product in Suspension Type

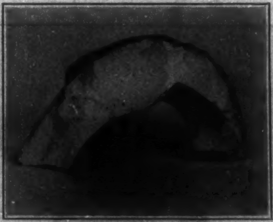

Fig. 10a

It is this type of insulator that is mentioned under Tests with High Frequency Oscillators, and goes to show that insulators can be made that will successfully withstand the tests shown, and there seems no reason why such insulators should not remain good in service for an indefinite period.

Maker E. Sample (3). 33,000-Volt Pin Type Insulator. This insulator successfully withstood all electrical tests both before and after having been subjected to the hydrostatic pressure tests, and when broken up, not the slightest sign of penetration of the dye could be seen; and the material was of a particularly good satin-like appearance.

Maker G. 33,000-Volt Pin Type Insulator. This also withstood all electrical tests, successfully, both before and after having been subjected to the hydrostatic pressure tests. When broken up, not the slightest sign of penetration could be seen, and this ranks as the finest sample of electrical porcelain seen by the authors.

11,000 Volt Pin Type Insulators

The testing of these insulators is regarded as particularly important, because they are within the range of local New Zealand manufacture, and the difficulty and cost of obtaining imported insulators during the war made it important that local insulators should be developed if possible. Investigations were made on those of two New Zealand makers (I and L) one Australian (K) and one American (E).

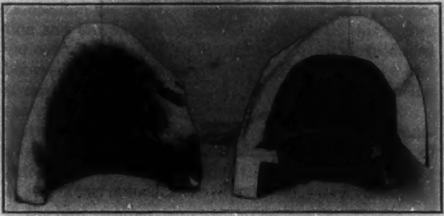

Fig. 11—Showing Local Products, on Left by Maker K (bad) and on right by Maker I (good)

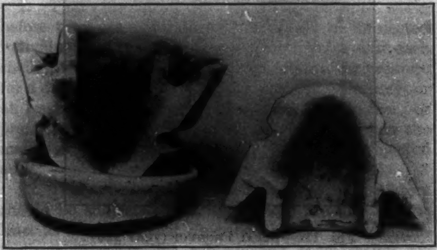

Fig. 11a—Local Product by Maker K. (Very Bad)

Maker E. Sample 4. This insulator punctured just below flashover during acceptance test, and was subjected to hydrostatic pressure test. Under this it showed distinct signs of penetration through the glaze, and particularly to a depth of about ¼ inch on each side of the puncture path, which was through the thickest part of the insulator, well down from the neck. Evidently there was a porous seam existing where the insulator broke down. Three other samples failed in the same way out of thirty selected at random from a shipment of 30,000, indicating a very high proportion of defective porcelain.

Maker K. A special batch of insulators by this maker failed to withstand even working pressure, and a few were subjected to the hydrostatic pressure test.

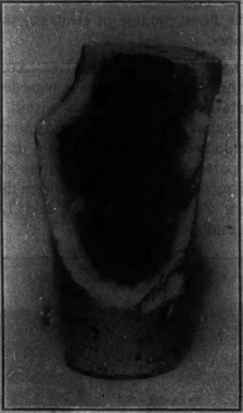

FIG. 11B—LOCAL PRODUCT BUS-BAR PILLAR (VERY BAD)

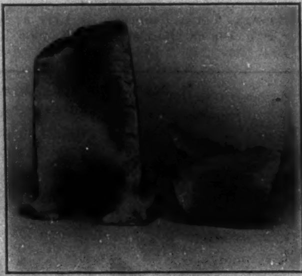

FIG. 11C—LOCAL PRODUCT (VERY BAD)

Figs. 11, 11A, 11B and 11C show broken samples after leaving the porosity vessel. It will be seen that the dye had penetrated deeply through the entire body, hence their puncture at such a low pressure. Apparently in this case no effective factory test whatever could have been employed.

New Zealand Manufacturers. The insulator by Maker I withstood all electrical tests successfully, both before and after being subjected to hydrostatic pressure test, and when broken up showed no sign of penetration. Later insulators have given equally good results, and the quality of the porcelain has apparently improved, indicating that local manufacture of this type of insulator is quite successful.

Another maker "L", after several attempts produced a very good insulator for use on low-tension work up to 500-volts, but for high-tension work failed distinctly, all his porcelain being porous.

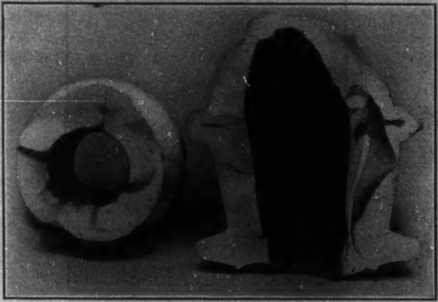

FIG. 12—MAKER M. SHOWING MARKED PENETRATION IN APPARENTLY A SEAM OF POROUS MATERIAL ON RIGHT AND A DEPTH OF ABOUT ¼ INCH FROM INSIDE EDGE ON LEFT

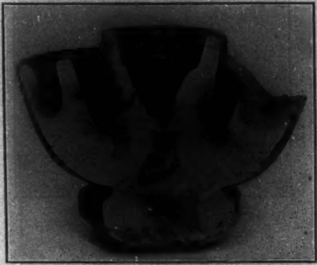

FIG. 12A—SHOWING SAMPLE OF HEAVILY GLAZED INSULATOR INTO WHICH THE DYE HAS BEEN FORCED THROUGHOUT THE ENTIRE MASS

Extra-High-Tension Bushing. A bushing for 66,000-volt circuits was supplied by Maker M—manufactured in England—who was seeking to enter the electrical field. It is assumed that the insulator was given some kind of test before being sent out such a distance, but on being tested electrically dry as received it punctured decisively in the thickest part, on approaching 40,000 volts. On being subjected to hydrostatic pressure test distinct signs of penetration were obvious, the dye being forced through the glazing to a depth of nearly

1/4 inch, and in the thickest part there was a distinct porous band, which had been apparently moulded with the insulator. Needless to say no further insulators were purchased from a manufacturer allowing such work to be exported. (Figs. 12 and 12A.)

Shape of Insulators. The shape of high-tension pin insulators has undergone a radical change since 1917, mainly on the lines suggested by Gilchrist and Kline Felter (*Electric Journal*, Vol. 15, No. 11, page 445). The original type adopted in the Lake Coleridge system, Fig. 13, manufactured by Maker B did not give good results owing to the shells practically enveloping each other so that it was impossible for the weather or wind to clean the inner shells, thus lowering the factor of safety of the insulator. In later designs the shells are more open so that not only is the weather able to displace such deposits, but the planes between the shells follow more closely the equipotential surfaces, and the body of the insulator conforms to the lines of electrostatic field as suggested by Gilchrist and Kline Felter.

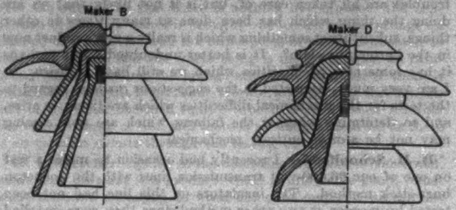

FIG. 13

This improved shape, coupled with the real improvement and greater consistency in quality of the porcelain has effected a substantial improvement in the life of the high tension insulators.

Glazing. Our experiments showed that glazing, even when over the entire shell of the insulator is no protection against impregnation by moisture. In the early stages of insulator manufacture apparently some importance was attached to the insulating quality of the glaze, and experience of puncture tests either in oil or in air tend to confirm this, in that when approximately the puncture value is reached, there is a definite time lag before the glaze starts to crack or craze, but when it does so, complete puncture quickly follows. Apparently then, the glaze has some value as a dielectric, but when once it breaks down it is no further protection, and when crazed, it is of course easily penetrated by moisture. Several of the figures herewith show penetration all along the glazed edges, indicating that the moisture must have entered through the glazed surface. We consider that our experiments demonstrate that glazing is no protection against the penetration of moisture, and that the insulator can be and should be made non-porous. Glaze should certainly not be put on to make good the defects of indifferent body material, and it will not do so.

General. The great importance of the transmission line insulator in the early construction days of most undertakings is usually lost sight of owing to the numerous urgent requirements of the rest of the plant, and as a rule, testing of insulators is left until trouble arises from breakdown on the transmission line. Extraordinary care is usually taken in testing the generators, water wheels, and other details, but the insulators are left to work out their own salvation, relying in some cases, quite without justification, on the makers' guarantees. The usual method is to dump the crates of insulators in the yard or alongside the poles, and leave them there exposed to the weather until they are ready for erection. During this period any porous insulators will certainly become more or less penetrated with moisture, and unless the factory tests are very thorough, trouble will ensue sooner or later. The authors consider that their observations indicate that there is need for much more co-operation between the manufacturer and the operating engineer with the object of reducing the maintenance. It is now general practise on the part of manufacturers to reduce as far as possible the stresses due to expansion and contraction and temperature variations, and with this object various types of jointing material have been introduced between the shells, which are intended to take the stresses due to temperature changes, thus reducing the cracking of shells due to such stresses.

Annual Overhaul. Annual overhaul on the transmission line is also very essential for the detection of defects not perceptible from the ground. This work of course has to be done as expeditiously as possible and in the best weather.

SUMMARY

From the tests and investigations described herein the following conclusions may be drawn:

1. That insulators for extra-high-tension work, before they are put into service should be subjected individually in the case of suspension units and on each shell in the case of pin insulators, to flash-over pressure for a definite period at both high and low frequency, or at least at high frequency, either by the maker, or preferably by the purchaser after delivery, when the maker should be prepared to bear the cost of rejected ones.

2. That a percentage of each shipment of insulators should be subjected to a hydrostatic pressure test at least as severe as that described herein. One manufacturer describes his competitor's specification for porosity as "a joke," and proposes instead a porosity test of 4800 lb-hours; which appears to the authors to be equally a joke.

3. That insulators can be made and are being made that will not be overstressed by such tests, and which should remain good in service for an indefinite period.

4. That a proportion of insulators supplied hitherto have been porous, and should be replaced at once by insulators that have been thoroughly tested.

5. Extreme care should be exercised in the selection

of the type and shape of insulator, having regard to the form of electrostatic field and to the self-cleansing form of the insulator.

6. There is room for more co-operation between the maker and the user in the matter of handling and maintaining insulator service.

7. That in a country such as New Zealand where it is proposed to develop hydroelectric power to the utmost limit of its resources, a public testing laboratory should be established, where various undertakings could arrange for tests herein described, thus giving them a guarantee that the material received would be of the best quality, and eliminate the annoyance and mistrust engendered in the public mind by insulator breakdowns.

We desire to express our most cordial thanks to Mr. L. Birks the Chief Electrical Engineer for the Dominion, for the support and help he has given us in this work. Much of the information contained in the paper is Departmental, and for permission to publish this we are indebted to him.

Our thanks are also due to The New Zealand Institute which gave us the monetary grant which enabled the porosity tests described to be developed.

Discussion

W. A. Hillebrand: I will confine my discussion principally to the paper by Messrs. Farr and Philpott. The energy and care with which they prosecuted this research is highly commendable, and the results are extremely interesting. On the other hand it is characteristic of a great deal of such work that an attempt is made to draw general conclusions from incomplete data. For example, the insulators on which they made their tests were evidently of very poor material.

Another factor which they have overlooked, and which is very frequently overlooked in such a series of tests is the time-puncture characteristic of the material. That must be known fairly well before one can obtain definite results. Of any lot of insulators a small percentage will puncture at dry flashover voltage. This percentage depends upon the quality of the porcelain, and is proportional at least to the first power of the time the voltage is applied. This always enters as an unknown factor in any series of tests involving periodic applications of voltage.

The insulators reported upon are of designs now largely obsolete, which has a bearing on the question of time constants and the superior ability of an oscillator to puncture under test, which has been known for a number of years. A long, deep shell similar to the type used in the earlier pin-type insulators manufactured ten years ago, may have a 60-cycle flashover of 50,000 volts. Under an impact or oscillation that flashover will run up to seventy-five, eighty thousand—perhaps double. The design is such that when a steep wave front is impressed upon it the porcelain withstands a very much higher flashover than do designs that are such as are used today, with consequently greater liability to puncture.

One very interesting thing which they bring out is that whole insulators were used in their porosity test, and that they succeeded in a very large number of cases in driving the fuchsine right through the glaze. That is not altogether surprising in view of the fact that the glaze is continuous with the porcelain body and of composition similar to the binding material in the porcelain itself. Except for the fact that it is on the outside and more exposed to the heat of the kiln, it should have a density similar to that of the body of the porcelain.

One fault to be avoided in such work is to draw conclusions from old material and attempt to apply them to ware as it is manufactured today. As a result, the authors are apparently in a mood to impose a rigorous specification upon the manufacturer, a procedure which often has been disastrous in the past. That is, an insulator can be designed to meet almost any requirement desired, but there is a very great danger, and it has very often happened, that such insulators will be very short-lived. There are a number of disastrous examples on record.

With regard to the possible cause of failure of insulators due to lap checks, sand streaks and so forth. One very interesting example of that was brought to my attention last year by an engineer who had dissolved the caps of a large number of insulators in acid. He showed me one shell that was absolutely down by the megger, which probably had a sandstreak or a lint streak in the head. Over many square inches of area he had with true Oriental patience, searched until he located a spot perhaps one-sixteenth of an inch in diameter, or less, where alone the porcelain was porous and down.

H. V. Carpenter: I am convinced that the manufacturers are now giving us some porcelain which is different from that which we have had in the past, and a great deal of data which we have had presented to us in past papers refer to the older type. Now the manufacturers will probably tell us that the old troubles are all taken care of, but is it not likely that we are doing the thing which has been done so many times in other things, substituting something which is really a new product now in the better porcelain? It is better undoubtedly but perhaps it has some new peculiarities which we still have to learn; so I am very much interested in the suggestions made in regard to the tests for the mechanical difficulties which are likely to arise, and to determine whether the failures which are now coming may not be almost entirely mechanical.

H. H. Schoolfield: I recently had occasion to make a test on one of our 66,000-volt transmission lines with the Johnston buzz-stick method. The insulators on this line had not been tested by megger or any other method since they were installed in 1912. I made the test this last spring and found only about three per cent of the insulators showed bad by that method. I consider this a very good record for a line built with insulators purchased in 1912.

There is no question but that we are getting a better grade of insulators now than we did then, and I expected to find a great many more failures than I did. The line was somewhat under-insulated too, compared to the way we insulate lines nowadays. It is a 66 kv. line with three cap and pin type units in suspension and four at strain points. One thing I did find though, that bears out some of the discussion this morning—that the larger percentage of failures was at the point of support, at the pole or cross-arm end of the string.

I also took a good many of the insulators that showed failure under the buzz-stick method, and checked them up with the megger after they had been taken down, and I am satisfied in my own mind that the megger does not give an accurate test; does not show accurately the bad insulators in the line. Some of the insulators that would show bad with the buzz-stick might show a high rating under the megger, but put on an oscillator test they would fail. Give them a high-potential test they would fail, although the megger did not show them bad.

There are a great many factors entering into testing with the megger. Atmospheric conditions, have to be watched very carefully, so I am very much inclined to favor a method similar to the buzz-stick for picking out bad insulators. I think a good many insulators might show bad under a megger test that should not be removed. A few years ago we made a practise of taking out an insulator from a string that would megger anything below 4000 megohms; between 3000 and 4000 megohms. Under that practise I think we took out a great many insulators that should not have been condemned. If we had left them in they would have stood up.

The line that I speak of, however, was in a very dry section of country, where we don't have very much rain. It wasn't in Portland, but was in the north central part of Oregon, around The Dalles. That may have had something to do with the low percentage of bad insulators we found.

R. J. C. Wood: Mr. Schoolfield's remarks have led me to think that it might be interesting to give a little outline of an instrument we have developed—under the direction of the engineers of the Southern California Company—to do the same work as the buzz-stick without some of the dangers that are inherent in its use. It seems to me that Mr. Schoolfield had his nerve with him when he used a buzz-stick on a line that had not been tested for so many years; with only three units on 66,000 volts. If he had happened to strike two bad units in the same string it would have resulted in an accident. In order to eliminate this danger, which is not so great on a 66 or 60,000-volt line where there are four units, but is very great on a 15,000-volt line where there are perhaps only two units, we made a little device, which is practically an electroscope. It is constructed of a piece of one-inch square bakelite tube with two vanes inside. Another electrode is wrapped around the central portion of that tube, the tube being a foot or so long, and some more square bakelite tube is slipped over the outside so that there is nothing hot exposed, the connection of the two vanes is brought out to one of the prongs on the end of the device and the outer piece of metal connected to the other prong, and the whole thing is mounted upon an insulating stick. Putting the prongs across an insulator if there is voltage across it the loops inside vibrate, and sighting through the end of the open one-inch square tube it is easily seen whether the vanes vibrate or not, and there is no danger incurred as there is no metallic circuit through the testing device.

H. L. Melvin: As far as the operating engineer is concerned, what they do want is a product which is uniformly good. Just what tests are necessary to weed out poor material we are not prepared to specify. Both design and tests are primarily manufacturing problems. The manufacturer must cooperate with the operating engineer to find out what the particular problems are. Operating companies are at fault in that until just recently, with the exception of a few of the larger companies, they have not kept records of failures or really studied the problem.

If we are now satisfied with the standard types of insulators it is the manufacturer's problem, to introduce as many logical improvements in the manufacturing and assembling of parts as they are able to devise to insure life to the insulator under operating, mechanical and electrical stresses. They must also devise tests which will insure the purchaser against the purchase of defective material.

However, I am convinced that further study of operating stresses both mechanical and electrical, must be made and tests devised to duplicate them. These tests may lead to a modification of the present general design as operating conditions become more severe.

Allen E. Ransom: During the war, I was Chief Electrical Officer, Major Commanding 137th Engineers at Base Section No. 1 St. Nazaire, and had occasion to use a good many insulators throughout that base. We were connected up with the French systems through the large Central Stations at St. Nazaire, Nantes, Angers, Saumur and other points. The Haviland works at Lyons were making insulators for the use of the American forces and put out a very fine grade of white porcelain insulator for 5000 and 20,000 volts. These with intermediate voltages were used on our temporary lines all through Base No. 1 and also at Brest and Bordeaux and the intermediate sections up towards the Front. We built something like 200 miles of primary and secondary lines and never had any insulator failures.

The machinery we had to use was mostly French which we obtained from the Westinghouse Works at Le Havre and the General Electric works at Lyons. We had no trouble with their motors and transformers at all. A great deal of the American machinery sent over was 2300 volts, 60 cycle. Standard French distribution primary voltage is 5000 volts, 3 phase, 50 cycle and 230 and 460 volts on secondary power circuits so American 60 cycle motors were all right.

The transmission lines throughout the Atlantic Coast section of France were almost all 20,000 volts and using power and light from steam turbine generating stations in the principal cities there being no hydroelectric stations in this district. Our experience with the French insulators was very satisfactory.

Conservation or Waste of Material in Educational Institutions

BY J. W. UPP
Member, A. I. E. E.
General Electric Company, Schenectady, N. Y.

THE successful operation of a republican form of government depends in large measure upon an educated people. It is obviously impossible to let the people rule unless their intellectual training has reached the point where they can distinguish between what is right and what is wrong. The better they are educated, the more likelihood there is that the governmental agencies will function in a proper manner.

These facts have been clearly recognized in this country ever since the present form of government was established with the result that our educational institutions have always received the active interest and support of an intelligent and generous people. We have pointed with pride to the country schools in which so many of our greatest men received their early educational training and have always given to such schools much of the credit for the successes achieved by those who attended them.

In other words, the American people have always believed so thoroughly in scholastic training that it was natural for them to exalt this work and to furnish funds for its continuance.

The same applies equally to the college and university. Early in our history we set up institutions of higher learning to supplement the work of the common or public schools and these institutions have constantly grown in number, size and importance to the present day.

The point we are trying to make is that no one without good reason would find fault with a system we all believed in. We do not believe, however, in all the details of its present day administration and accomplishments. We are forced to conclude that although our system of education has an uncounted number of highly commendable features, it has also some faults which should be corrected.

In discussing the work of the educational institution as regards the conservation or waste of material, we shall compare its activities and results to those of a modern manufacturing establishment. We shall do this because it is a convenient method to illustrate the points we have in mind.

Is it fair to draw comparison between a modern manufacturer and a modern educational institution? To the writer it seems quite in order to do so. Modern business is conducted on a very high ethical plane and directed by men of education and ability who must meet the keenest competition and have their accomplishments measured by actual values. The most efficient management is the one which obtains the largest amount of high grade finished product at moderate cost from a given amount of raw material. Surely there can be no objection to applying this standard to measure our educational institutions.

In a successful manufacturing establishment, close attention is always given to the material which will enter into the finished product, and the most careful specifications are drawn to insure the material purchased being of a grade suitable for the article which is to be produced. And these specifications are always supplemented by rigid inspection of the material when it is received. When the material has been accepted, it is the obligation of the management to use it to advantage and through efficient direction to obtain the maximum number of finished articles. It is also the duty of the management to use to advantage all by-products, and to salvage the material which has been damaged in handling or through careless workmanship, or which may have been spoiled by workmen who are not properly instructed or supervised.

Do our educational institutions accept the responsibilities for output that they should accept? Do they give the same attention to conservation of material that is a necessity in ordinary business undertakings? To the writer, it does not appear that they do and it is the purpose of this paper to draw attention to what appears as a profitable point for consideration.

Our educational institutions are furnished with the finest grade of material that the world produces. This material is selected under rigid specifications. It is not accepted until it is found of the grade that is considered suitable for the product that is desired. It comes to the educational institutions under the very best conditions with the certainty of every assistance that can possibly be given to maintain the standard. Every young man who enters an educational institution comes with the unqualified backing of family and friends and the kind of backing that should be of the greatest value. What is done with this material after it is received? It is beyond understanding that in the first period of the freshman year it is found that the material which has been selected under such carefully prepared specifications is defective to so large a degree. It is equally disturbing to find there is further rejection in the succeeding periods of freshman, sophomore, junior and even senior years. Is the fault with the material? If so, there are serious faults in the specifications. Is

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Presented at the Pacific Coast Convention of the A. I. E. E., Vancouver, B. C., August 8-11, 1922.

the fault with the handling of the material? If so, the methods of handling are inefficient.

The writer in looking over the records of many of the highest grade educational institutions cannot find a single one which to a business man would be considered satisfactory. The results, if duplicated in a modern business, would be the cause for criticism and there would be certain failure.

Is the comparison unreasonable? Is it proper to ask that the college or university give a better accounting of the resources which are under its immediate direction?

Each year, we find very great attention being given to the size of the entering classes, also attention to the number of those who have received degrees and diplomas; but has there ever been a published statement at commencement as to the number who have failed to complete the work which they started four years earlier? How many of our instructors would be commended if they pointed to a class which had completed the course without a failure? How many of our professors would feel that they had properly conducted their work if they did pass every one in their classes? How many accept personal responsibility for the failure of any individual under their supervision who does not complete the prescribed work in a satisfactory manner?

The selection and training of the teacher is probably the most important phase of college administration. The teaching professions is justly recognized as of very great importance. It calls for leaders of the highest type. The mere ability to impart to the student the information contained in the text books is only one of the requirements. There must also be wise sympathetic and forceful leadership to direct the students' efforts or there will be much confusion, conflict and waste. On every staff and in every faculty there are many with all the fine characteristics that are required. Of these, we wish to voice our appreciation and to commend the success they have obtained in directing the students along paths which have been so productive. The teacher to be of maximum value must have a tremendously vital interest in his subject and in the great responsibility of his position. He should be of a type which appeals strongly to a vigorous, energetic young man, of a type which takes as much interest in student affairs as the student himself. How, otherwise, can he hold their interest and how, otherwise, can he make them believe that the things he teaches are worth while?

The teacher must be selected with great care and must then receive a sufficient salary to enable him to take his proper place in the community. He must be a successful man himself if he can ever be hoped to teach success to others. The difference between the successful and the unsuccessful teacher is certainly not determined entirely by the book knowledge each possesses. It depends largely on their comparative attributes for real leadership.

These leaders are necessary. How to obtain them, I leave for the college authorities to decide. That they do not exist in sufficient numbers at this time is evidenced by the results obtained.

One of the greatest wastes of human material in connection with our colleges results from the student following the wrong course. This is also one of the most difficult things to remedy.

The particular courses the students take depend to some extent upon the family's general desire to have them enter some certain profession. Very little detail or analytical study is given to the problem. The courses selected are usually determined by the relative popularity of some branch of engineering, law, medicine, etc., and have no relation whatever to the actual capabilities of the prospective students. The individual characteristics of the students, the type of training they have had in their homes, the ever changing needs of social, intellectual and industrial life, complicate the problem tremendously and make its attempted solution worthy of the deepest study.

The purpose of a college is to give an education to those who enter its doors but of what that education should properly consist is surrounded by much hesitancy and doubt.

The subjects for study and the arrangement of the courses have always received considerable attention but there is still much to be done along this line. When it is necessary to force the sudents into studying subjects which they cannot see will be of advantage to them in later life, it is obviously very difficult to hold their interest. On the other hand, the students will give all the necessary time and intensive study to those things that interest him deeply. To create that interest is one of the most important duties that is met successfully by the real teacher. When the students fail, the teacher must take most of the blame.

It cannot be said that the educational institutions have not had the backing of the people, and that it is, therefore, difficult to obtain sufficient funds to pay for a sufficient number of teachers to give the students individual attention.

If the financial support received has been insufficient to meet the requirements, it is because of a weak presentation of the case. The people of this country will not knowingly let their educational institutions suffer if the matter is put before them in the proper light.

A college or university should be run according to the best modern business principles. That is, the administrators should be able to show a satisfactory return on the investment. The stockholders of any business corporation would soon withdraw their support if it should appear that the management was inefficient in carrying on its affairs; and the college or university will naturally receive the same treatment.

There is no doubt that even after the most careful selection, some of the material will be found defective, but can it not be used in some other manner? It will also be found that some of the material has been damaged in handling, but that too, can be usually repaired or used for some other equally valuable service. Some material too becomes defective because it has been handled by careless workmen or by workmen who have not been properly instructed and it is this material which it would appear should have the most attention.

That errors have been made in reference to this material which has been rejected as unsatisfactory, there can be no doubt. In the writer's experience, there have been many cases where not only has the damage been repaired, but later the material has been found of the most excellent grade, in some cases of such high grade that it required special attention in order that it might be most effectively used. It was rejected because its qualities were not understood, not because it was defective.

The modern manufacturer has a research department which devotes the entire time to finding ways of using to advantage materials which have heretofore been of little service, also to use materials where the results desired have not been obtained. Is there not a parallel work for educational institutions? Cannot a division of college work be made which would make it possible for a group of men connected with the faculty to study the causes of failure, to make the new applications, to revise the methods or change the work so that the ability of the individual could be properly developed and applied?

The writer has had an opportunity to observe young men and young women under various conditions,—those who have been marked as successful and those who have been marked as unsuccessful,—but in almost every case careful selection has given satisfactory results, and in practically every case it has been possible to encourage the individual to do what he set out to do and to accomplish the thing that was desired.

One of the most common causes of failure in the earlier years of educational work seems to be the improper direction of those who are immature. It would seem in order to apply more stringent regulations to those who are far from the years of discretion, and it certainly would be in order to do this if the results should prove that such regulations were warranted.

No doubt if the writer was actively engaged in directing the work of an educational institution, he would find the problems overwhelming. But as a business man, the solution of those problems would always be desired and sought for until the percentage of finished product was many degrees higher than it is in our educational institutions at this time. There is no desire to lower in any degree the very high standards which have been set. There is no desire to recommend that diplomas be given for work that has not been completed, but there is a firm belief that with different methods with more study given as to the causes of failure, it would be possible to effect a very considerable saving of material.

Is there a college or university today which is advertising the fact that anything short of 100 per cent output is viewed as a matter of concern, which has found the reasons for failure and is applying the remedies, which is holding itself up as a standard of excellence because its output is equal to its input?

We know of no such institution. We doubt if it exists. We doubt if it will ever exist, but we shall be satisfied that our colleges and universities are properly directed only when this condition is far more closely approximated than it is at the present time.

We wish to say again that there is not, nor can be, a more worthy purpose than the proper education of every young man and young woman, and everything should be done which can be of assistance in this direction.

Waste in every form should be eliminated.

Discussion

For discussion of this paper see note, page 639.

Training to Think Versus Gathering Information

BY TALIAFERRO MILTON

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THE time allotted to me is not sufficient for me to go into details of how I have arrived at my conclusions, and I will, therefore, content myself with the expression of some of my opinions.

Many professional educators may not agree with me and I shall be very glad indeed to debate the subject with them in such detail as cannot be used in this short summary of my opinions.

I regret that I have not any very useful suggestions of a constructive nature to offer to educators in regard to what should be done to correct and improve the systems of education now in use in this country. If, however, these mere expressions of opinion will serve to stimulate the professional educators in discovering cures for the evils which are patent to many of us engaged in practical every-day work, then what I have to say will be worth something.

I do not claim any originality in these opinions; in fact they have been formed not only through my own personal observations, but through many discussions with other work-a-day men with whom I have come in contact. I left the educational field because I did not think I was suited to it, and all I can do is to point out to professional educators evils for which they may, through their study and experience, find a cure.

The crime of most of the colleges today is that they do not teach their students to think. They spend too much time in cramming facts into the student's heads when, in my opinion, the short four years available to the average student for college life is all too little time for teaching the student to think. After all, it really doesn't matter very much whether a young man in the early 20's leaving college, knows a great deal of a concrete nature, provided he has learned to think.

It is of course, necessary that certain fundamental principles be taught; moreover, they should be drilled into the heads of the students, but beyond that, the work to be performed by a student should always be laid out with the one idea in mind of increasing the student's capacity and ability to think. Why should time be wasted in college, in shop work? What does it matter whether or not a young fellow, graduating from college, can file a flat surface or do a good blacksmithing job, or a hundred other odd mechanical jobs, unless the doing of such jobs is entirely incidental to the training of his thinking apparatus? Suppose he *is* a fair mechanic when he leaves college—he will find in the shops mechanics who have never even been through high school who are ten times as good as he is at a hundred different jobs. These mechanics who have had little schooling have learned every step in their trade in an empirical fashion and I have known some of them who were crammed full of a thousand and one facts some of which were not true. Not long ago I was talking to an older man about a certain young fellow, and I remarked that this young man seemed to have had a lot of knowledge. The older man answered, "Yes, he knows a lot, but unfortunately most of it isn't true."

Several of the cleverest engineers with whom I am acquainted spent most of their time in college on one piece of research work and when they started their careers as engineers, they were very *very* "green" from the shop-man's and practical engineer's viewpoint. They had practically no acquaintance with the thousand and one details of shop equipment, central station equipment, etc. However, the particular piece of research which each had done had involved a great deal of study and thought and in completing this research they had learned to think. Before making the research, they had, in each case, been thoroughly drilled in the fundamental underlying principles of mathematics and physics which were the tools they used in thinking out the problem in hand. The fact remains that (without going into further detail of how I have arrived at these conclusions) these men today *are* great constructive engineers. I know other men who have never had any college education who are also great engineers and I find that they are great thinkers.

I go so far as to believe that if a man is born a great thinker it matters not whether he has any college education. Some extreme examples are John Marshall, the great Chief Justice, and Abraham Lincoln, the great "Emancipator" and President. These men, to be sure, were not engineers, but I think none of us doubt that had they turned their hand to engineering instead of law and politics they would have been just as successful in the engineering field as they were in their chosen professions. Those of you who have read biographies of these men, especially the recent "Life of John Marshall" by Senator Beveridge, cannot help but be impressed with the fact that even though these men obtained very little standard education in the common schools and colleges they did get in their particular scheme of study and work a tremendous training in how to think.

Right here I want to say that I believe there should be no fundamental difference between the general methods of engineering education and education for any other profession. All education for the young man during his school and college courses should be with the one idea in mind—to increase his capacity for thinking straight, thinking clearly and thinking ener-

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getically through each problem to a conclusion. Once he has acquired such a habit, each problem will be conquered as it arises regardless of how much concrete knowledge on the subject one has to start with. This reminds me of a definition of an engineer which was given to me some time ago by an engineer who is a member of this Institute. He said, "An engineer is one who learns how to do something before the people find out that he doesn't know how." It is obvious that he couldn't function in this manner unless he were trained in the fundamental principles and knew how to think.

No one could claim that an exact knowledge of a great many facts is in itself detrimental. My whole contention is that the time is so short in the grammar school, high school and college that the teaching of empirical knowledge should not crowd out the training in the thinking processes and it has been my direct observation that that is exactly what has happened to a large percentage of college graduates. Their minds have been crammed full of facts and they are unable to think clearly. A man taught a lot of facts can only copy work previously done. He will never build anything new, unless along with these facts he has learned how to think. He cannot produce synthetic results because he cannot think things out to a conclusion. He has become mentally lazy because others have done his thinking for him and have supplied him with the finished result in the form of a fact.

A student, even if he starts with an inclination to think will soon abandon effort in that direction if he is drilled by his professors to accept their teachings as immutable laws. The student should be trained at all times to keep his mind open. He should never be allowed to accept any working hypothesis as an indisputable law. The best picture I know of the danger of teaching students that the working hypotheses which we now accept as laws are indisputable and immutable is contained in the French astronomer Flamarion's little story, at the end of his chapter on the LaPlace Nebula Hypothesis. Those of you who are not familiar with this story will, I am sure, get something out of it and I recommend that you look it up.

The overemphasis which, in my opinion, is being given to the laboratory method seems to have extended backward into the high school and grammar school. I say extended backward because I believe that the prodigious use of the laboratory method now in vogue in the grammar and high schools is because of the entrance requirements of the colleges. I have a fine opportunity just now of observing the methods in the grammar school because I have two children in one of the finest public grammar schools in America. It certainly seems to me that the laboratory method is being overworked.

While I believe that a large part of the trouble with most of our college graduates today is due to the waste of time in teaching them facts, I would like to point out what, in my opinion are other indirect causes of the student's lack of thinking capacity. One of the main troubles with modern colleges, especially the large ones is the lack of democratic spirit. Above all things we should make the college really democratic and drill into the student's heads that all they obtain at college is a training in the groundwork and the fundamental principles and the process of real thinking so that when they leave college they are ready to *start* life's work. The college student, who starts life's work with an idea that because he has been to a certain college he is better than other men has a serious handicap and he loses several years in getting a fresh start.

Some years ago I sent my business card into the office of a young engineer who had quite an important position with a large concern in the northwest. He came out into the reception room and his greeting was, "Are you a salesman or an engineer? I do not care to talk to a salesman; I want to talk to one of your company's engineers." I asked him, "Are you an engineer?" and drawing himself up stiffly, he said, "I am a graduate of —" (naming one of our largest and best known engineering colleges). I had difficulty in restraining the explosion which began to accumulate in my insides. I got to be quite friendly with this fellow but I learned in a short time that he was not an engineer at least not one in accordance with the definition I have given above. It so happens that the college he was graduated from has turned out a great many thinkers, but I have often wondered whether they learned to think at college or whether they were just born that way, or whether some good old-fashioned teacher in the grammar or high school started them off right so that even the college couldn't ruin them. *Lack of the democratic spirit is not conducive to clear thinking.*

A college should teach modesty. Most modest men are thinkers. Perhaps that's the reason they are modest and perhaps I am mixing up the cause and effect.

I have in mind several of the smaller colleges in this country who are turning out men, the great majority of whom seem to be able to think; and in looking around for a cause of this I have noticed that the men at these colleges work. The athletic and social side is not over exaggerated as it is in some of the larger and wealthier colleges. If the athletic and social functions are made of too much importance, a man hasn't time to think. When he isn't attending a football game or a dance, he is trying to cram up sufficient "*facts*" to pass his examination.

Everything that is said above could apply as well to any other form of education as it could to engineering education and I believe that other branches of education are just as derelict in these respects as is the modern form of engineering education.

Some of the college courses for engineers are, however, even worse than the college courses for other professions in that they slur over the teaching of English, literature, philosophy and history. I know some pretty good, practical engineers who are college graduates and who get pretty good results, but who are almost illiterate. I do not believe that many of us agree with one of our most prominent automobile manufacturers that such education is useless. Certainly those of you who agree with me that the main principle of education should be enhancing a man's thinking capacity cannot admit that a broad education is not necessary in an engineering course. What can stimulate the thinking powers more than a good general knowledge of literature, philosophy and history?

Summing up, it is my firm opinion that in the United States today we are overdoing empirical, shop and laboratory practise in our educational institutions all the way from the beginnings of the kindergartern through the university. I believe that by overdoing these methods we are cramming the student's minds instead of enlarging them.

Teach the student to think and give him just such facts as are necessary to make him think.

Discussion

For discussion of this paper see note, page 639.

Engineering Graduates in Business

BY L. A. FERGUSON

Fellow, A. I. E. E.

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IN a business in which engineering talent is required to produce its output or operate its plants, the engineering graduate is looked to as the supply of timber from which to build up the personnel of the technical and supervisory forces. Without a capable personnel no organization can be effective, and without knowledge such as the engineer is trained to use in an accurate way, no such business can make headway against its competitors.

The engineering graduate has been trained in the fundamentals of pure science and mathematics, and has been given an acquaintance with applied sciences which, if he has been conscientious, has provided for him the foundation of his future work. He is started in his first position as a draughtsman, inspector, laboratory assistant, tester, or in some similar line of work where he will be able to render service of some value while he is learning enough about the business to fit him for a position of responsibility. In some cases he may be shifted from one minor job to another several times before he is definitely placed. In other cases he may voluntarily shift from one business to another in the hope of finding something which looks more promising. In this process he discovers work for which he has an aptitude and in most cases the work is of a specialized nature in which he makes use of but a small part of the knowledge gained in school. The result is that those whose natural talents qualify them to excel at highly technical kinds of work are chosen promptly for such work, giving the impression that the highly technical man is the one most sought after and desired.

A considerable part of the men who entered with a given class and whose talents run rather to construction and installation work, or to sales engineering, have either fallen by the wayside under the discouragement of the tests encountered, or, if graduated, have drifted away after a time into some other line of activity where their talents are better appreciated. Men of the latter class may be and often are those having business ability, and after the first few years they are likely to be found in positions of greater responsibility than those whose ability as students was much more marked. Every class of any large engineering school which has been out of school for five to ten years affords examples of this.

There are, of course, the exceptional men who were good students and had also the talents for the larger positions in life, and these exceptions but prove the rule.

Thus in the past decade there has been a distinct tendency to develop a large body of engineering technicians who are highly skilled in the treatment of special problems and who have as a result contributed in a large way to the sum of human knowledge. But too many of these men have become so highly specialized that they have lost the breadth of view which is essential to a proper sense of perspective and are, therefore, incapable of seeing the broader problems of industry or of suggesting solutions for them.

Now, how is a recital of conditions affecting graduates of engineering schools in past years related to the education and training of the coming generation? The answer is that history will repeat itself unless changes are made in the general scheme of education in the future.

The training of the student has been conducted thus far from the point of view of giving him a general fund of technical knowledge. This is perhaps only the natural result of an atmosphere where scholarship is made the chief criterion of excellence, and other lines of ability are largely subordinated to it.

The training of the students of the future should make provision for the type of men who though they may not shine in technical work will nevertheless take places of importance in the industrial world where leadership, salesmanship, and executive ability are in great demand.

It is true that men of this type will usually make a place for themselves in the world whether they enter engineering schools or not, but the engineering world

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is losing many men under present conditions whom it will very much need in the coming years.

The engineering courses as at present constructed appear to be unattractive to this type of men and we find many of the sons of graduates of the last generation substituting courses in general science for engineering courses in order to get more of the general culture of a college training, and to come more into touch with the the non-technical life of the school.

Just how the details of engineering courses should be modified to make them more attractive to this class of students I do not presume to say, but it would seem that the elective courses could have a broader scope and the required work could be made less exacting than has been the custom in most schools.

The situation may be likened in many respects to the conduct of a saw mill enterprise, conducted by a lumber company which is cutting its own timber. The business is covering the rough pine lumber market for general construction purposes and its mill and other facilities have been planned for this business exclusively. It turns out heavy timber for railroad and mill construction and smaller shapes for building purposes and general uses. Its supply of timber is chiefly pine, but there are occasionally "stands" of certain kinds of hardwood which yield logs of higher value than the general run of pine, and though a few of these come through with the rest, the majority are left standing. The mill is not equipped to handle these few properly for the hardwood market, so they go into the output and are sold with the pine. The consumer finding these occasional pieces of hardwood is not able to take advantage of their increased value and they are hidden in a structure where their worth is not likely to be recognized by the owner. Occasionally it is true such a piece comes to the attention of a foreman by chance, and after proper seasoning and finishing operations is given a place befitting its value. After a time, the mill owners realize they are losing a valuable part of their output, and provide for proper finishing of their hardwood as it passes through. It is thereafter turned out in such shape that it can be seasoned and finished for the more important uses to which it is adapted. This makes it possible for the lumber company to take the hardwood with the pine, thus clearing up the entire stand of available timber as it goes.

The available timber entering the universities and engineering schools has many things in common with the stand of timber described in the foregoing illustration.

If technical experts are to be the chief output of the schools the timber which doesn't make good ones will be and is being eliminated as it goes through. And if perchance a few exceptional men get through who are capable of being more than technicians, they are as likely as not to become buried in the technical work so deeply that the fact that they are capable of greater responsibilities is not discovered until a long time after it should have been known.

The establishment of a course designed for treating the hardwood, that is, the men who do not aim to take positions where the work is highly technical, will perhaps not result in any output of men of any higher average ability than are graduated from other courses, but it should serve to increase the available supply of timber for general uses, for which there is now a firm demand with a diminishing supply.

Discussion

For discussion of this paper see note, page 639.

Exciter Instability

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PART I—DISCUSSION OF THE PROBLEM

A. Introductory

INSTABILITY of an exciter has come to have a number of meanings: (1) large change in voltage for a small change in load; (2) creeping of voltage, up or down, without apparent cause; (3) temporary removal, partial or total, or even reversal of the excitation accompanying sudden short circuit of the alternator; (4) slow oscillation, or possibly reversal, of excitation following a sudden readjustment of either the shunt field or alternator field rheostat;[1] (5) "grabbing" the load, etc. when in parallel with other exciters. The last mentioned trouble, which is experienced largely, although not altogether, on compound-wound machines does not occur if respect is given to well-known characteristics of direct-current machines as discussed in any text book on the subject. Therefore this paper deals only with the first four phenomena mentioned above.

Experience. All these phenomena have occurred in actual practise. While they have been relatively rare and not confined to exciters of any particular manufacture, there have been enough cases where the consequences have been serious, such as the shut-down of large generating units, to warrant investigation into the causes and character of the phenomena.

Experience has shown that these phenomena occur when the exciter is operating at low magnetic densities; that is, below or near the bend in the saturation curve as at *e* or below, in Fig. 1.

Historical. In 1920 a number of Institute papers[2] were read on exciters and excitation systems. These papers were largely statements of experience and of opinions as to the factors which should predominate in the selection of an excitation system. One of them[3] however, dealt fully with certain phases of exciter design, particularly with reference to successful operation with automatic voltage regulators. In the same year a paper by Kelen[4] discussed the reversal and loss of residual magnetism of exciters, giving equations which showed voltage reversal, under a certain assumed current transient. However, it appears that there has not been a comprehensive mathematical study of the particular system of circuits involved in this problem to determine the behavior of the exciter under conditions which may arise in practise.

Scope. The present investigation comprises (a) a mathematical study of circuits involved, as shown in Fig. 2, assuming the exciter is operating within the range of the straight portion of the saturation curve; and (b) an experimental confirmation of the calculated results. From these two viewpoints it is possible to draw definite conclusions as to the influence upon stability, of the different design features of the exciter and alternator and of the circuits involved.

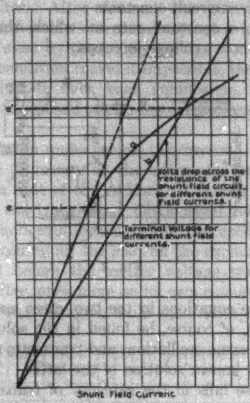

FIG. 1

B. Form of Equation

The most interesting and fundamental result of the investigation is the fact that the differential equation relating the alternator field current with time, is identical in form with the classic differential equation of the electric circuit involving resistance, inductance and capacity. Thus in the present case the equation relating the alternator field current with time is,

$$\frac{d^2 i_2}{d t^2} + \alpha \frac{d i_2}{d t} + \beta i_2 = A \text{ (amperes/sec.}^2\text{)} \quad (7)$$

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[1] "Reversal of Exciter Polarity" M. A. Walker, *Power*, June 12, 1917, V. 45 pp. 792-793.

"Trouble with Directly Connected Exciters Due to Polarity Reversal" G. Rutherford, *Electrical World*, Mar. 18, 1916. V. 67, pp. 658, 659.

[2] These are given in the accompanying bibliography.

[3] "Application of D-C. Generators to Exciter Service," by C. A. Boddie and F. L. Moon, from A. I. E. E. JOURNAL, Vol. 39, 1920, pp. 1595-1616.

[4] Elektrotechnik und Maschinenbau, May 16, 1920, V. 38, pp. 225-226.

where

i_2 = alternator field current

t = time

α and β = constants depending upon circuit constants as defined by equations (**8**) and (**9**)

A = constant depending upon the *sustained* value of exciter voltage as defined by equation (**10**).

The classic equation of the electric circuit involving resistance, inductance and capacity is

$$\frac{d^2 i}{d t^2} + \alpha_e \frac{d i}{d t} + \beta_e = A_e \qquad \text{(amperes/sec.}^2\text{)}$$

where i = current in the circuit

t = time

α_e = constant = r/L

β_e = constant = $\dfrac{1}{LC}$

A_e = constant = E/L

r, L and C = circuit constants

E = constant rate at which the impressed voltage increases.[5]

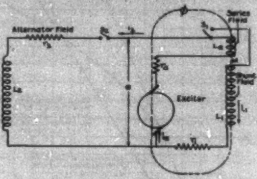

FIG. 2

Since the equations in the two cases are identical, there must, of course, be found in the solution of the former the same oscillations and transients as are given in the well known solution of the latter. That is, the present case falls in the category of transients designated by Steinmetz as "double energy" transients.[6] In other words, if on the one hand an exciter is closed upon an alternator field circuit, and on the other hand, a voltage which increases in direct proportion to time is suddenly impressed upon a circuit containing resistance, inductance and capacity, then one may expect the current as related to time to be of precisely the same form in either case. Depending upon the relation of circuit constants the current may gradually build up to a final value, or may finally reach this value after a number of progressively smaller oscillations.

Transients of the same character will also occur if a sudden readjustment of circuit constants is made, which is equivalent to suddenly impressing a different voltage. Thus Fig. 6 shows a transient oscillation following the application of the exciter voltage to an alternator field circuit; Fig. 14, the oscillation following a sudden readjustment (increase in resistance) of shunt field rheostat; Fig. 16, the gradual (logarithmic) decrease of current to a final value following a similar sudden increase in shunt field rheostat, but with different circuit constants; Fig. 9, the surge and decay of current following a sudden short circuit of the alternator, which, as explained in Part II, is equivalent to a sudden change in circuit constants.

It will be observed that while these transients are of the same form as those of the electric circuit containing resistance, inductance and capacity, they are of much longer duration and lower frequency.

C. CONDITIONS FOR INSTABILITY

Conditions of instabilty are; low magnetic densities,[7] in combination with one or more of the following:

(a) low residual voltage.

(b) relatively large voltage drop in the armature, due either to large demagnetizing component of armature reaction or to large ohmic resistance in the armature circuit between the points where the shunt field terminals are connected.

(c) relatively large inductance in the load circuit, such as always exists in the alternator field.

(d) alternator transient of greater duration than exciter transient.

(e) excessive series field strength.

Discussion of Conditions. Consider the conditions of low magnetic densities. It is well known that a saturated exciter is usually stable since it requires a relatively large change in ampere turns to produce a given change in the magnetic flux. The degree of stability is roughly gauged by the magnitude of the angle θ, Fig. 3. The operating point p on the saturation curve is determined by the condition that the $r\,i$ drop of the shunt field circuit shall equal the terminal voltage of the exciter. Above that point, the terminal voltage is less than that required to sustain the shunt field current; below, it is more than required. That is, the greater the angle θ the more stable the exciter. It is thus obvious from Fig. 3 that on the straight portion of the saturation curve, the stability is low; and if it were not for the residual voltage e_0, θ would be zero and the exciter would be inoperative; that is, a single value of shunt field resistance would correspond to *all* voltages on the straight portion of the curve.

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[5] That is, $e = E\,t$. This merely determines the final value of current, and has nothing to do with the character of the transient, since the transient is determined by making $A_e = O$. It was so chosen in this illustration to make the two cases exactly parallel, including both the transient and the final value.

[6] In the circuit containing r, L and C, the "double energy" refers to the two forms of energy storage $1/2\,L\,I^2$ and $1/2\,C\,E^2$.

In the present case, while there is no condenser capacity involved, and therefore no electrostatic energy, there are nevertheless two different magnetic circuits—alternator and exciter fields—in which energy can be stored. Obviously, in an oscillation all of the relatively large energy in the alternator field cannot be transferred to the small exciter field. Most of it is dissipated as $i^2\,r$. Only a small percentage is transferred to the exciter, but it is sufficient to start the exciter to build up again, the energy supplying the subsequent oscillations thus coming from the mechanical drive of the exciter.

[7] That is, operation on straight portion of the saturation curve.

Thus it follows that residual voltage is essential to stability in operation on the straight portion of the curve. However, operation beyond the bend, that is involving a significant degree of saturation, would be stable with zero residual voltage.

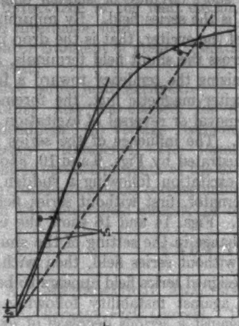

FIG. 3

The condition of large voltage drop in the armature means a large droop in the volt-ampere characteristic of the exciter, Fig. 4. Curves *a* and *b* are volt-ampere characteristics of the particular exciter used in this investigation; *a* being for normal brush position, *b* for a forward shift of 2.7 mechanical degrees. Curve *c* is the volt-ampere characteristic of the receiving circuit, that is, it gives the voltage required to maintain the current i_2 in the resistance r_2 of the receiving circuit, which in the present problem is the alternator field circuit. The exciter must obviously operate at the intersection of the volt-ampere characteristics of the exciter and receiving circuit. The unstable condition of relatively large voltage drop in the armature is thus illustrated in Fig. 4 by the intersection of *b* and *c*, that is the point *n*. Stability could evidently be obtained by increasing r_2, which would increase the slope of *c*, moving *n* upward to a less steep portion of curve *b*; or, with the same r_2, a change in the exciter characteristic to correspond to *a*, thus giving the stable intersection *m*.[8]

The existence of a large inductance in the load circuit, which means relatively large magnetic energy storage is the fundamental condition for the occurrence of "double energy" transients as distinguished from slow "creeping" of voltage. This energy storage makes possible a "pump back" of power into the exciter under certain conditions. For instance, any sudden condition which tends to lower the exciter voltage—such as the large load current thrown on the exciter when the alternator is short-circuited, or a sudden increase in the shunt field rheostat, or a decrease in the alternator field rheostat—such conditions cause the load current of the exciter to decrease. But the large inductance in the alternator field will not permit the current to decrease as rapidly as it would if its decrease were determined by the exciter alone. Thus under certain conditions the alternator field tends to hold the decreasing load on the exciter always at a higher value than the decreasing voltage of the exciter could alone maintain, and when zero magnetic flux in the exciter is reached, the current is maintained through the armature by the external voltage generated by the alternator field. This means that the voltage across the armature and therefore across the shunt field is reversed, and thus the voltage builds up reversed. While it is reversed, and before the decreasing current reaches zero, the alternator field is obviously supplying power to the exciter. After reversal the alternator field inductance holds the current always at a *lower* value than would exist by the exciter voltage alone. Therefore such a condition makes it impossible, theoretically, for the exciter to ever reach equilibrium. Actually, of course, it is reached after a few oscillations, as shown in Fig. 7.

The condition under which this reversal may occur is that the duration of the alternator transient is greater than that of the exciter. It is thus a race between these two transients. Obviously if the alternator tends to reach equilibrium before the exciter, its influence in holding up the load on the exciter will have disappeared before the exciter voltage reaches zero, and the exciter, once more on its own resources, if only for a moment, will again build up. Thus the inductance of the alternator field makes possible oscillations and voltage reversals; and the condition under which this is possible is that the duration of the alternator transient is greater than that of the exciter.

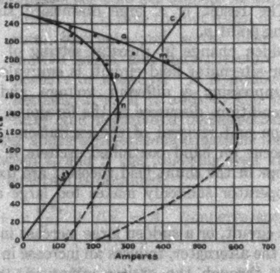

FIG. 4

Excessive series field strength obviously gives to the exciter characteristics approaching those of the series generator. Such characteristics may be obtained as well by connecting a normally designed exciter on a receiving circuit of too low resistance, as by designing for too great series field strength. For instance, a 125-volt exciter connected to an alternator field requiring only 60 volts for normal exciting current, (rated current on exciter) means practically doubling the relative strength of the series field; and quadrupling the strength, assuming the same kilowatts excitation.

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[8] This, of course, is merely reciting, in the interest of completeness, a fact already given in text books.

D. CAUSES OF INSTABILITY

The principal causes are:

(a) speed transients

(b) temperature transients

(c) slight undulations in exciter voltage, which may modify the local effect of hysteresis and thus cause a gradual shift in the saturation curve and a corresponding change in voltage.

(d) sudden, relatively large change in rheostat setting.

(e) short circuit of the alternator.

Discussion of Causes. The first three causes may produce voltage "creeping," the last two "double energy" transients. The effect of speed transients, which is to shift the operating point p Fig. 3 on the saturation curve, is discussed in the paper by Boddie and Moon, loc. cit.

Temperature transients produce slow voltage changes in a similar manner. Rising temperature, and therefore increasing resistance, in the shunt field circuit slowly increases the slope of the $i_1 r_1$ line Fig. 3, but does not change the saturation curve. It thus shifts the point p downward.

Slight undulations in the exciter voltage[9] mean repeated traversal of the local hysteresis loop, which, by this process, moves the center of the loop gradually toward the *average* saturation curve, thus in effect eliminating or seriously reducing the residual magnetism. The result is a large downward shift in the operating point p.

A sudden change in rheostat setting of either the shunt or alternator field circuit, is equivalent to suddenly impressing a different voltage, and therefore under conditions discussed in the foregoing, may cause oscillation and reversal of the excitation. This may easily occur on hand controlled exciters if the resistance steps in the shunt field rheostat are too large, or if the operator suddenly makes too large an adjustment.

Short circuit, or a sudden large increase in inductive load on the alternator, induces an increase in the direct current[10] through the exciter armature—that is, an increase in load, the greater the current increase in the alternator armature. This initiates the "double energy" transients already discussed.

E. STABILIZERS

Voltage "creeping" can be minimized by special design to increase the angle θ Fig. 3 at low voltages. The same result can be obtained by a few cells of a storage battery in series with the shunt field, thus giving the effect of greater residual voltage, e_0, Fig. 3. Separate excitation of the shunt field by storage battery gives practically perfect stability, but of course involves obvious disadvantages.

The most effective stabilizer against shocks due to alternator short circuits, or sudden change in circuit constants, is the series field. By minimizing the voltage drop of the exciter, that is the drop in voltage impressed across the shunt field terminals, and therefore also minimizing the tendency toward a further reduction of exciter magnetic flux, the foremost factor in causing removal or reversal of excitation is practically eliminated. The influence of the series field in these cases is illustrated by Figs. 9 and 10, showing respectively the excitation following a sudden short circuit of the alternator, first without series field, then with series field. Figs. 14 and 16 show the excitation following a change in the setting of the shunt field rheostat, first without series field, then with. That is, a properly designed series field appears to be the greatest protection against instability following shocks, particularly against a serious decrease of excitation, and therefore of synchronizing power of large generating units under short-circuit conditions.

The next is the automatic voltage regulator. Its effect is to instantly decrease the shunt field resistance, that is, to greatly decrease the slope of $i_1 r_1$ Fig. 3, thus adjusting the exciter instantly for a greater load. In other words, when an exciter transient starts, the regulator instantly introduces a rapid transient in the opposite direction, and therefore stabilizes the exciter under most conditions arising in practise. Its influence on the exciter following a short circuit of the alternator is shown in Fig. 13. The combination, therefore, of a properly designed compound wound exciter controlled by an automatic voltage regulator, gives excellent stability.

Resistance in the alternator field circuit increases stability by shortening the alternator transient and lengthening the exciter transient[11], thus doubly increasing the ratio of the durations of these transients. If sufficient resistance is put in the alternator field circuit, the exciter voltage may reach values above the bend of the saturation curve, and so further increase the stability by saturation. Figs. 9 and 11 show respectively the transient following a short circuit on the alternator, first without and then with a rheostat in the alternator field circuit.

F. SUMMARY

1. The form of equation for exciter voltage and current is the same as the well known equation for the

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[9] This might be caused by speed variations as on direct-connected or belted exciters driven by reciprocating machines such as steam or gas engines, or compressors.

[10] There is also an alternating component, but its frequency is too high to significantly affect the exciter flux.

[11] By causing the exciter to operate at a higher voltage, thus requiring lower resistance in the shunt field circuit.

electric circuit containing resistance, inductance and capacity. Hence the same form of oscillations and transients are involved, the only difference being that in the present case the duration of the transients is much longer.

2. Instability may occur when the exciter is operating on the straight part of the saturation curve, if in addition some combination of the following conditions exists:

(a) very low residual voltage—say 1 per cent or so.

(b) a relatively large voltage drop in the armature.

(c) large inductance in the load circuit, as always exists in the alternator field.

(d) alternator transient of greater duration than the exciter transient.

(e) excessive series field strength.

3. Instability may be classed, for convenience, under two headings: (a) voltage "creeping," and (b) "double energy" transients. The former may be caused by slight speed transients of the exciter; or by temperature transients causing corresponding resistance transients in the shunt field circuit; or by hysteresis effects which may be caused by small undulations in the exciter voltage. The "double energy" transients, such as oscillations and reversal of excitation, may be initiated by a shock, such as a short circuit on the alternator, or sudden, relatively large change circuit in constants, for instance a large change in resistance in the shunt field circuit.

4. The exciter can be stabilized against voltage "creeping," (a) by special design to increase the angle θ Fig. 3 at low voltage; (b) by a few battery cells connected in series with the shunt field, thus giving the effect of greater residual voltage e_0 Fig. 3; (c) by separately exciting the shunt field; (d) by automatic voltage regulator; or (e) by rheostat in the alternator field, requiring the exciter to operate at voltages involving saturation. It can be stabilized against "double energy" transients (a) by a properly designed series field; (b) automatic voltage regulator, or both (a) and (b); (c) alternator field rheostat.

The author wishes to acknowledge the valuable assistance of Mr. R. F. Franklin in the preparation of this paper.

PART II—EQUATIONS AND TESTS

A. MATHEMATICAL ANALYSIS

Equation for Alternator Field Current. The following assumptions are made:

Constant speed of exciter
Operation below bend of saturation curve
Residual voltage, constant
Resistance of armature circuit, constant.

Fig. 2 shows the arrangement of circuits and defines the different currents, voltages and circuit constants.[12] The differential equations for the voltage in the different circuits are as follows:

Alternator field circuit,

$$e = i_2 r_2 + L_2 \frac{d i_2}{d t} \qquad \text{(volts)} \qquad (1)$$

Exciter shunt field circuit,

$$e = i_1 r_1 + L_1 \frac{d i_1}{d t} + M \frac{d i_a}{d t} \qquad \text{(volts)} \qquad (2)$$

Exciter armature circuit,

$$e = e_a - i_a r_a - M \frac{d i_1}{d t} - L_a \frac{d i_a}{d t} \qquad \text{(volts)} \qquad (3)$$

Also,

$$i_a = i_1 + i_2 \qquad \text{(amperes)} \qquad (4)$$

where,

e_a = generated voltage of exciter
r_a = ohmic resistance of exciter armature circuit[13] including series and interpole fields, if any.

Assuming that the exciter is working at low magnetic densities, *i. e.*, on the straight part of the saturation curve, the equation for the generated voltage is,

$$e_a = e_0 + K \phi \qquad \text{(volts)} \qquad (5)$$

where,

ϕ = flux per pole in magalines
K = total generated armature volts per megaline of flux per pole.
e_0 = residual voltage.

The flux ϕ is a function of both the shunt field current and the armature current. Thus,

$$\phi = k_1 i_1 + k_a i_a \qquad \text{(megalines)} \qquad (6)$$

where,

k_1 = megalines per pole per shunt field ampere
k_a = megalines per pole per ampere in the armature circuit. It is thus the net result of the armature, interpole and series field magnetomotive forces, and may therefore be either positive or negative. It is positive if magnetizing, *i. e.*, if it adds to the shunt field flux; and negative if demagnetizing.

Solving the above simultaneous equations for the relation between i_2 and t, the following well known differential equation is obtained:

$$\frac{d^2 i_2}{d t^2} + \alpha \frac{d i_2}{d t} + \beta i_2 = A \qquad \text{(amperes/sec.}^2\text{)} \qquad (7)$$

where,

$$\alpha = \frac{r_2 (L_a + M) + r_1 (L_a + L_2) + [r_a - K (k_1 + k_a)] (L_2 - M) - [K k_a - (r_a + r_2)] (L_1 + M)}{(L_2 - M) (L_a + M) + (L_1 + M) (L_a + L_2)} \qquad \text{(1/sec.}^2\text{)} \qquad (8)$$

$$\beta = \frac{- K (k_1 r_2 + k_a r_2 + k_a r_1) + r_a r_2 + r_1 r_a + r_1 r_2}{(L_2 - M) (L_a + M) + (L_1 + M) (L_a + L_2)} \qquad \text{(1/sec.}^3\text{)} \qquad (9)$$

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[12] For detailed definition see "notation."

[13] Armature circuit up to the points where the shunt field terminals are connected.

$$A = \frac{e_0 r_1}{(L_2 - M)(L_a + M) + (L_1 + M)(L_a + L_2)} \quad \text{(amperes/sec.}^2\text{)} \qquad (10)$$

Equation (7) is a second order, linear differential equation whose solution, as given in all texts on differential equations, is,

$$i_2 = C_1 \epsilon^{m_1 t} + C_2 \epsilon^{m_2 t} + A/\beta \quad \text{(amperes)} \qquad (11)$$

where, C_1 and C_2 are integration constants, and

$$m_1 = -\alpha/2 + \sqrt{\alpha^2/4 - \beta} \quad \text{(1/sec.)} \qquad (12)$$

$$m_2 = -\alpha/2 - \sqrt{\alpha^2/4 - \beta} \quad \text{(1/sec.)} \qquad (13)$$

Let,

$$\gamma = \sqrt{\alpha^2/4 - \beta} \quad \text{(1/sec.)} \qquad (14)$$

and,

$$i_0 = A/\beta$$

$$= \frac{e_0}{(r_2 + r_a) + r_2/r_1 [r_a - K(k_1 + k_a)] - K k_a} \quad \text{(amperes)} \qquad (15)$$

Substituting these relations in (11) the final equation for the alternator field current becomes,

$$i_2 = \epsilon^{-\frac{\alpha}{2} t} (C_1 \epsilon^{\gamma t} + C_2 \epsilon^{-\gamma t}) + i_0 \quad \text{(amperes)} \qquad (16)$$

Integration Constants

The integration constants C_1 and C_2 will be determined for four different boundary conditions.

Case I. Switches S_1 and S_2, Fig. 2, are closed at the same instant.

Thus at $t = 0$, $i_1 = 0$, $i_2 = 0$, $e = e_0$.

Hence from (16)

$$C_1 + C_2 + i_0 = 0. \quad \text{(amperes)} \qquad (17)$$

Another relation between C_1 and C_2 is necessary. This is given by equation (1). Since at $t = 0$, $i_2 = 0$.

$$\frac{d\,i_2}{d\,t} = e_0/L_2 \quad \text{(amperes/sec.)} \qquad (18)$$

Differentiating (16) and substituting $t = 0$,

$$\frac{d\,i_2}{d\,t} = m_1 C_1 + m_2 C_2 \quad \text{(amperes/sec.)} \qquad (19)$$

Equating (18) and (19)

$$m_1 C_1 + m_2 C_2 = \frac{e_0}{L_2} \quad \text{(amperes/sec).} \qquad (20)$$

Solving (17) and (20) for C_1 and C_2, and substituting (12), (13) and (14)

$$\left.\begin{aligned} C_1 &= \frac{e_0/L_2 - i_0(\gamma + \alpha/2)}{2\gamma} \\ C_2 &= -\frac{e_0/L_2 + i_0(\gamma - \alpha/2)}{2\gamma} \end{aligned}\right\} \quad \text{(amperes)} \qquad (21)$$

Case II. After switch S_1 has been closed and the exciter voltage has built up to its permanent value, close S_2, Fig. 2.

Thus at $t = 0$, $i_2 = 0$, $e = e'$ where e' is the exciter terminal voltage previous to closing S_2. Hence from (16)

$$C_1 + C_2 + i_0 = 0 \quad \text{(amperes)} \qquad (22)$$

and from (1)

$$\frac{d\,i_2}{d\,t} = e'/L_2 \quad \text{(amperes/sec.)} \qquad (23)$$

Since (22) and (23) are identical in form with (17) and (18), the integration constants for Case II are, by analogy with (21),

$$\left.\begin{aligned} C_1 &= \frac{e'/L_2 - i_0(\gamma + \alpha/2)}{2\gamma} \\ C_2 &= -\frac{e'/L_2 + i_0(\gamma - \alpha/2)}{2\gamma} \end{aligned}\right\} \quad \text{(amperes)} \qquad (24)$$

Case III. Switches S_1 and S_2 have been closed and the currents i_1 and i_2 have reached the permanent values i_{11} and i_0 respectively. Short circuit occurs on alternator.

In this case the boundary values are taken as those existing the instant after the alternator short circuit and are determined by the condition that neither the magnetic interlinkages with the alternator field winding nor that with the shunt field circuit can change, in the first instant, from the values existing before the short circuit occurred. That is, the alternator field flux which, before short circuit traversed the low-reluctance path through the armature iron, inductance L_2, must now pass through the higher reluctance of the leakage paths, inductance L_2', between field and armature windings. But since the magnetic interlinkages of this circuit[14] has not changed.

$$L_2 i_0 = L_2' i_2'$$

where $i_2' = L_2/L_2' \, i_0$ (amperes) (25)

There is also, of course, a large alternating component of current through the exciter armature, but its effect on the exciter is practically negligible, since the frequency is so high. Likewise, since the flux ϕ[15] linked with the shunt field circuit has not changed, it is by (4), (6) and (25)

$$\Phi = \overbrace{k_1 i_{11} + k_a (i_{11} + i_0)}^{\text{before}} = \overbrace{k_1 i_{11}' + k_a (i_{11}' + i_2')}^{\text{after}} \quad \text{(magalines)} \qquad (26)$$

From (25) and (26)

$$i_{11}' = i_{11} + i_0 (1 - L_2/L_2') \frac{k_a}{k_1 + k_a} \quad \text{(amperes)} \qquad (27)$$

Thus at $t = 0$, $i_2 = i_2'$, $i_1 = i_{11}'$

From (16)

$$C_1 + C_2 + i_0 = i_2' \quad \text{(amperes)} \qquad (28)$$

Another relation is necessary. This is given as before, by

$$\frac{d\,i_2}{d\,t}$$

at $t = 0$. Substituting in (2) and (1) respectively equation (4) and the values of i_1 and i_2 at $t = 0$, as determined by (25) and (27), and equating, a relation is obtained between $\frac{d\,i_1}{d\,t}$ and $\frac{d\,i_2}{d\,t}$. It is,

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[14] Equation (25) neglects the relatively small inductance L_a of the exciter armature circuit.

[15] Strictly this should be magnetic interlinkages instead of *flux*, since the flux may increase due to partial interlinkages in the leakage paths. However, the approximation is justified in the present case, since the change in flux is relatively very small.

$$\frac{d\,i_1}{d\,t} = \frac{i_2\,r_2 - i_{11}'\,r_1}{L_1 + M} + \frac{L_2' - M}{L_1 + M}\,\frac{d\,i_2}{d\,t} \qquad \text{(amperes/sec.)} \qquad (29)$$

Equating (1) and (3) and substituting (4), (5), (26) and (29),

$$\frac{d\,i_2}{d\,t} = G = \frac{e_0 + i_{11}'\,[K\,(k_1 + k_a) - r_a] + i_2'\,(K\,k_a - r_a - r_2) - \dfrac{L_a + M}{L_1 + M}\,(i_2'\,r_2 - i_{11}'\,r_1)}{(L_a + L_2') + \dfrac{L_a + M}{L_1 + M}\,(L_2' - M)} \qquad \text{(amperes/sec.)} \qquad (30)$$

Thus from (11) and (30)

$$\frac{d\,i_2}{d\,t} = G = m_1\,C_1 + m_2\,C_2 \qquad \text{(amperes/sec.)} \qquad (31)$$

Solving (28) and (31) for C_1 and C_2, and substituting (12) and (13)

$$\left.\begin{aligned} C_1 &= \frac{G + (i_2' - i_0)\,(\gamma + \alpha/2)}{2\,\gamma} \\ C_2 &= -\,\frac{G - (i_2' - i_0)\,(\gamma - \alpha/2)}{2\,\gamma} \end{aligned}\right\} \qquad \text{(amperes)} \qquad (32)$$

In calculating α and β from (8) and (9), the value of leakage inductance L_2' should, of course, be used instead of the total inductance L_2.

Case IV. Switches s_1 and s_2 have been closed and i_1 and i_2 have reached the permanent values i_{11} and i_2'' respectively. The shunt field resistance r_1 is suddenly changed from r_1^0 to r_1'.

As in Case III, boundary values are taken as those existing the instant after r_1 is changed, and are determined by the condition that the magnetic interlinkages of shunt field and alternator field circuits must, for the moment, each remain the same. It is necessary to know i_2 and $\frac{d\,i_2}{d\,t}$ at $t = 0$.

$$i_2 = i_0 \quad \text{and} \quad \frac{d\,i_2}{d\,t} = 0.$$

The latter may not be obvious. In the first instant, that is at $t = 0$, the exciter flux ϕ has not changed. $\frac{d\,\phi}{d\,t}$ is not zero, but at $t = 0$ no appreciable change has occurred. Hence e has not changed, neglecting the insignificant voltage $M\,\frac{d\,i_1}{d\,t}$, and therefore i_2 has not changed.

From (1), $\frac{d\,i_2}{d\,t} = 0$. Therefore from (11) and (16) at $t = 0$,

$$C_1 + C_2 + i_0 = i_2'' \qquad \text{(amperes)} \qquad (33)$$

$$\frac{d\,i_2}{dt} = m_1\,C_1 + m_2\,C_2 = 0 \qquad \text{(amperes/sec.)} \qquad (34)$$

Solving (33) and (34) for C_1 and C_2, and substituting (12), (13) and (14),

$$\left.\begin{aligned} C_1 &= \frac{(i_2'' - i_0)\,(\gamma + \alpha/2)}{2\,\gamma} \\ C_2 &= \frac{(i_2'' - i_0)\,(\gamma - \alpha/2)}{2\,\gamma} \end{aligned}\right\} \qquad \text{(amperes)} \qquad (35)$$

That is, the same as for Case III when $G = 0$. In calculating i_0 from equation (15), substitute r_1' for r_1; in calculating i_2'' from (15), substitute r_1^0 for r_1; and in calculating α and β from (8) and (9) respectively, the total inductance L_2 should be used, as in Cases I and II.

Consider the character of C_1, C_2, m_1 and m_2. These may be either real or imaginary since each contains γ, which may be either real or imaginary depending upon whether $\alpha^2/4$ is greater or less than β. As discussed in texts on differential equations, if the exponent γ is real the solution involves only logarithmic functions, if imaginary it involves a combination of logarithmic and trigonometric functions, *i. e.*, a decaying oscillation.

If γ is real, the form of (16) is satisfactory for numerical calculation. However, if it is imaginary it becomes necessary to rewrite (16) in a different form for calculation.

For the latter case, that is when

$$\alpha^2/4 < \beta$$

let $\quad \gamma' = \sqrt{\beta - \alpha^2/4} \qquad$ (1/sec.) $\qquad$ (36)

Then $\quad \gamma = j\,\gamma' \qquad$ (1/sec.) $\qquad$ (37)

The constants of integration in all four cases are of the form

$$\left.\begin{aligned} C_1 &= \frac{a - j\,b}{j\,c} \\ C_2 &= -\,\frac{a + j\,b}{j\,c} \end{aligned}\right\} \qquad \text{(amperes)} \qquad (38)$$

where in

Case I

$$\left.\begin{aligned} a &= e_0/L_2 - \alpha/2\,i_0 && \text{(amperes/sec.)} \\ b &= i_0\,\gamma' && \text{(amperes/sec.)} \\ c &= 2\,\gamma' && \text{(1/sec.)} \end{aligned}\right\} \qquad (39)$$

Case II

$$\left.\begin{aligned} a &= e'/L_2 - \alpha/2\,i_0 && \text{(amperes/sec.)} \\ b &= i_0\,\gamma' && \text{(amperes/sec.)} \\ c &= 2\,\gamma' && \text{(1/sec.)} \end{aligned}\right\} \qquad (40)$$

Case III

$$\left.\begin{aligned} a &= G + \alpha/2\,(i_2' - i_0) && \text{(amperes/sec.)} \\ b &= -\,\gamma'\,(i_2' - i_0) && \text{(amperes/sec.)} \\ c &= 2\,\gamma' && \text{(1/sec.)} \end{aligned}\right\} \qquad (41)$$

Case IV

$$\left.\begin{aligned} a &= \alpha/2\,(i_2'' - i_0) && \text{(amperes/sec.)} \\ b &= -\,\gamma'\,(i_2'' - i_0) && \text{(amperes/sec.)} \\ c &= 2\,\gamma' && \text{(1/sec.)} \end{aligned}\right\} \qquad (42)$$

Thus in all four cases the equation for i_2 is by (**16**)

$$i_2 = \epsilon^{-\frac{\alpha}{2}t} \left[\frac{a - j\,b}{j\,c}\,\epsilon^{j\gamma' t} - \frac{a + j\,b}{j\,c}\,\epsilon^{-j\gamma' t} \right] + i_0 \qquad \text{(amperes)} \qquad (43)$$

But, by Euler's relation,

$$\left.\begin{aligned} \epsilon^{j\gamma' t} &= \cos\gamma' t + j\sin\gamma' t \\ \epsilon^{-j\gamma' t} &= \cos\gamma' t - j\sin\gamma' t \end{aligned}\right\} \qquad \text{(numerical)} \qquad (44)$$

Substituting (**44**) in (**43**),

$$i_2 = 2/c\;\epsilon^{-\frac{\alpha}{2}t}\,(a\sin\gamma' t - b\cos\gamma' t) + i_0 \qquad \text{(amperes)} \qquad (45)$$

or, simplifying,[16]

$$i_2 = \frac{2\sqrt{a^2 + b^2}}{c}\,\epsilon^{-\frac{\alpha}{2}t}\sin(\gamma' t + \theta) + i_0 \qquad \text{(amperes)} \qquad (46)$$

where $\theta = \arctan(-\,b/a)$ (radians)

Exciter Voltage

From equation (**1**)

$$e = i_2\,r_2 + L_2\,\frac{d\,i_2}{d\,t} \qquad \text{(volts)} \qquad (1)$$

As discussed in the foregoing, there are two cases to consider: (1) when γ is real, and (2) when γ is imaginary.

(1) when γ is real. Use equation (**16**).

Thus

$$i_2 = \epsilon^{-\frac{\alpha}{2}t}\,[C_1\,\epsilon^{\gamma t} + C_2\,\epsilon^{-\gamma t}] + i_0 \qquad \text{(amperes)} \qquad (16)$$

Differentiating (**16**),

$$\frac{d\,i_2}{d\,t} = \epsilon^{-\frac{\alpha}{2}t}\,[\,(\gamma - \alpha/2)\,C_1\,\epsilon^{\gamma t} - (\gamma + \alpha/2)\,C_2\,\epsilon^{-\gamma t}] \qquad \text{(amperes/sec.)}$$

Hence from (**1**)

$$\begin{aligned} e = \epsilon^{-\frac{\alpha}{2}t}\,[\,\{r_2 + L_2\,(\gamma - \alpha/2)\}\,C_1\,\epsilon^{\gamma t} + \{r_2 \\ - L_2\,(\gamma + \alpha/2)\}\,C_2\,\epsilon^{-\gamma t}] + i_0\,r_2 \end{aligned} \qquad \text{(volts)} \qquad (47)$$

C_1 and C_2 being determined by—

(21) for Case I.
(24) for Case II.
(32) for Case III.
(35) for Case IV.

(2) when γ is imaginary. Use equation (**45**).

Thus,

$$i_2 = 2/c\;\epsilon^{-\frac{\alpha}{2}t}\,(a\sin\gamma' t - b\cos\gamma' t) + i_0 \qquad \text{(amperes)} \qquad (45)$$

Differentiating (**45**),

$$\frac{d\,i_2}{dt} = \frac{\epsilon^{-\frac{\alpha}{2}t}}{c}\,[\,(2\,\gamma' b - \alpha\,a)\sin\gamma' t + (2\,\gamma' a + \alpha\,b)\cos\gamma' t] \qquad \text{(amperes/sec.)}$$

Hence, from (**1**)

$$\begin{aligned} e = \frac{\epsilon^{-\frac{\alpha}{2}t}}{c}\,[\,&\{2\,r_2\,a + L_2\,(2\,\gamma' b - \alpha\,a)\}\sin\gamma' t \\ &- \{2\,r_2\,b - L_2\,(2\,\gamma' a + \alpha\,b)\}\cos\gamma' t] \\ &+ i_0\,r_2 \end{aligned} \qquad \text{(volts)} \qquad (48)$$

where a, b and c are determined by—

(39) for Case I.
(40) for Case II.
(41) for Case III.
(42) for Case IV.

B. DISCUSSION OF ASSUMPTIONS

Fig. 2 shows the circuits considered. The equations therefore apply strictly to an individual exciter connected to an alternator field, and not to a number of exciters in parallel. However, if the exciters in parallel have the same characteristics, and operate at constant speed, as assumed, then the group can be considered as a single unit with constants as resultant of those of the several exciters; and the alternator field connected to the bus can be considered as a single circuit with resultant constants. Then the equations will apply.

However, the object of the equations is much less to calculate the behavior of exciters in service than to investigate and determine, once for all, the factors which cause unstable exciters and the factors which make them stable. Because, if an exciter is stable when operating as an individual unit under the shocks of alternator short-circuit and other conditions, here considered, it may be safely assumed that it will also be stable when in parallel with others.

Do not misunderstand. Load "grabbing," etc., due to lack of respect for fundamental characteristics of d-c. machines when making connections or adjustments of such machines in parallel, is not considered. It is not fair to blame the exciter for "grabbing" the load or reversing if thrown on the bus at too low or too high voltage, or if it is not properly "equalized." No one would blame an engine for running away if its governor were out of adjustment. This sort of "instability" is not considered, and in the other respects which are considered, an exciter which is stable as an individual unit can be regarded as stable also when in parallel.

The fact that the alternators operate in multiple does not significantly affect the behavior of the exciters under the conditions considered.

Constant speed is assumed. A change in speed will produce a transient in the voltage designated in Part I as "creeping." This transient may be determined from the equation by using the value of e_0 and k_1 corresponding to the new speed, and substituting the existing currents, etc., before the change as boundary conditions to determine integration constants. In this type of transient the voltage differences which sustain the transients are very small. In the other type *i. e.,* "double energy" transients, due to shock, such as alternator short circuit, the voltage differences involved in the transients are very large. Therefore in the latter case, any small variations in voltage due to slight speed change, being a small percentage of the large voltage difference involved, do not materially affect the results as calculated on the assumption of constant speed.

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[16] For plotting results (**45**) is perhaps the better form, because although it requires two curves to be plotted, there is no difficulty in keeping signs straight, as there may be if (**46**) is used.

Operation on the "straight" part of the saturation curve, and a constant residual voltage are assumed. That is, the saturation curve is expressed by the linear equation (**5**). Actually, the curve, especially on small exciters, is neither absolutely straight at the lower densities nor does it have a constant intersection e_0 as residual voltage. Hysteresis determines both. However, the curve is *approximately* straight, and the residual *approximately* constant, sufficiently so to warrant the assumption—particularly, since the purpose is not to calculate magnitudes with great accuracy, but only to investigate the character of phenomena and the factors upon which they depend. Thus it will be observed that the tests in this respect compare well with the calculated results. If an oscillation is predicted, it occurs. Its frequency may be different, but it is an oscillation. Just so for logarithmic transients. But in the main, even magnitudes are close.

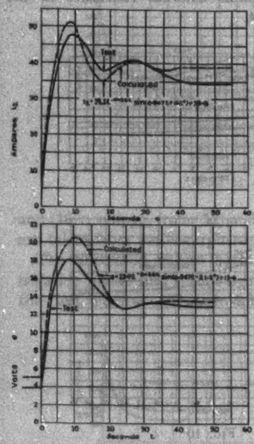

FIG. 5

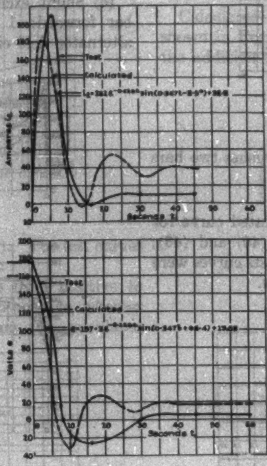

FIG. 6

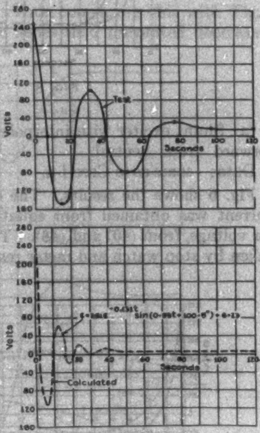

FIG. 7

C. CALCULATIONS AND TESTS

Calculations and tests were made on a 25,000 kv-a. 25-cycle 300-rev. per min. alternator excited by a six-pole compound-wound, interpole, 150-kw., 1200-rev. per min., 250-volt, induction-motor-driven exciter.

Tests were made as far as possible under conditions of the four different "Cases"[17] for which integration constants were determined. Change of constants in each different Case[18] was also made with corresponding calculations and tests.

The data substituted in the equations for results to compare with tests, are calculated[19] from designs of the exciter and alternator.

Tests

Case I. Switches S_1 and S_2 closed at the same instant. See Fig. 2.

(a) Shunt exciter[20] with interpoles; brushes two bars (3.5 mechanical degrees) forward[21] *from the neutral position.*

Data:[22] $L_1 = 37.6$
$L_2 = 1.69$
$L_a = 0.000075$
$M = -0.055$
$k_1 = 0.805$
$e_0 = 5$
$r_2 = 0.35$
$r_1 = 68.2$
$r_a = 0.015$
$K = 82.0$
$k_a = 0.00125$

Fig. 5 shows the calculated and test results. With the above constants, γ is imaginary. Hence the calculated curve for current was obtained from equations (39) and (46); voltage, from (39) and (48). The test curves are taken from oscillograph records.

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[17] Thus Case I, Case II, etc.

[18] Case Ia, Case IIa, etc.

[19] Except k_a, which was measured.

[20] Series field omitted.

[21] In direction of rotation.

[22] For definition of symbols see "D. NOTATION."

Case II. After switch S_1 has been closed and the exciter has built up to permanent condition, S_2 is closed.

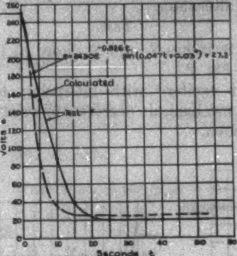

Fig. 8

(a) Shunt exciter with interpoles; brushes two bars forward from neutral.

Data: same as in Case I a.

Fig. 6 shows the results. The calculated curve for current was obtained from equations (40) and (46); for voltage, from (40) and (48). The tests curves were taken by stop watch and meter readings.

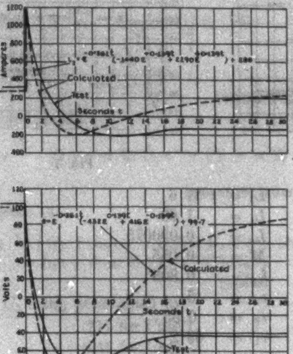

Fig. 9

It will be observed that the current and voltage actually pass through negative values before finally settling at positive values.

(b) Shunt exciter without interpoles; brushes 1/2 bar forward.

Data: Same as in Case Ia, except:

$k_a = -\ 0.00317$
$r_1 = 67.3$
$M = -\ 0.142$
$r_a = 0.013$

Fig. 7 shows voltage transient. The calculated curve was obtained from equations (40) and (48). The test curve was taken by stop watch and meter readings.

It will be observed, as in Case IIa, the voltage passes through negative values before finally settling at positive values. The lower frequency of the test curve as compared to the calculated curve is probably due to slowing up of the transient by hysteresis as explained under "B. Discussion of Assumptions."

(c) Shunt exciter without interpoles; brushes 1/2 bar forward: 1.35 ohms external resistance in the alternator field circuit.

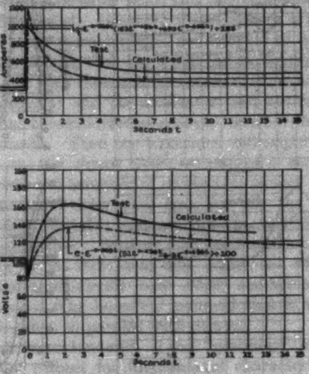

Fig. 10

Data: Same as Case IIb, except, $r_2 = 1.70$.

The voltage transient is given in Fig. 8. The calculated curve was obtained from equations (40) and (48). The test curve was taken by stop watch and meter readings.

In contrast with Case IIb, it will be observed that the voltage does not oscillate and pass through negative values in going from the one condition to the other. The large increase in alternator field resistance r_2 sufficiently increases the relative magnitude of α with respect to β (see equations (8) and (9)) to make

$$\gamma = \sqrt{\alpha^2/4 - \beta} \text{ real.}$$

Case III. Switches S_1 and S_2 have been closed and currents i_1 and i_2 have reached their permanent values. Alternator suddenly short-circuited.

(a) Shunt exciter with interpoles; brushes two bars forward.

Data: Same as Case Ia except:

$r_1 = 51.2$

$L_2 = L_2' = 0.42$

Fig. 9 shows the calculated and test results. With the above constants γ is real. Hence the calculated curve for current was obtained from equations (**32**) and (**16**); voltage, from (**32**) and (**47**). The test curves are taken from oscillograph records.

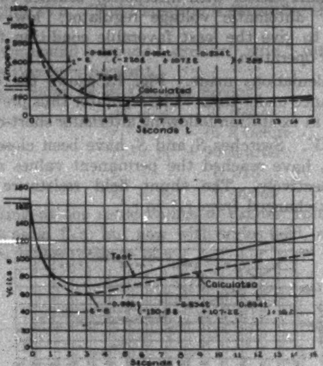

Fig. 11

The calculated curves both pass from positive to negative values and return again to positive, whereas the test curves, although following the calculated reasonably close to the maximum negative value, nevertheless do not return to positive values but remain negative. This is explained by the fact that the equation assumes the residual voltage e_0 to be constant and thus always positive. Hence the current and voltage must, by the equation always return to positive values Actually, however, the residual reverses when the voltage and current reverse and hence in this case the test curves remain negative.

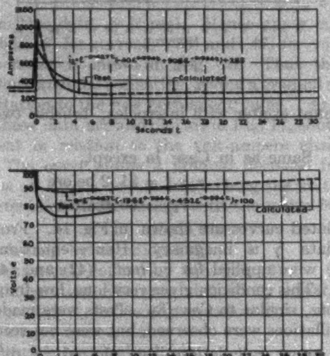

Fig. 12

If it appeared worth the trouble, the equation could be made to apply by step calculations. That is, a second set of boundary conditions could be taken as those existing at maximum negative e, *i. e.*, at $t = 4$ seconds, Fig. 9, and reversing the sign of e_0.

(b) Compound wound exciter with interpoles; brushes two bars forward.

Data: Same as in Case IIIa except:

$k_s = + \ 0.00055$

$r_1 = \ 76.2$

$r_s = \ 0.016$

$M = + \ 0.0247$

Calculated and test performance of the exciter is shown in Fig. 10. Thus comparing this with Fig. 9, the addition of the series field prevented decrease of excitation under the condition of sudden short-circuit of the alternator.

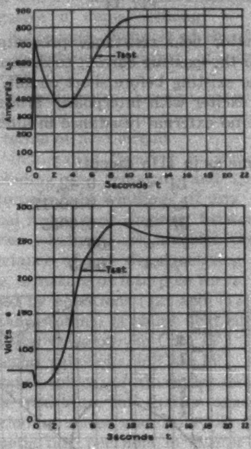

Fig. 13

The calculations were made by the same equations as in Case IIIa, and the test curves were taken from oscillograph records.

(c) Shunt exciter with interpoles; brushes two bars forward; 0.22 ohms external resistance in alternator field circuit.

Data: Same as in Case Ia except:

$r_2 = 0.57$

$L_2' = 0.42$

$r_1 = 56.0$

Performance curves in Fig. 11. Calculations from same equations as in IIIa; test curves from oscillograph records.

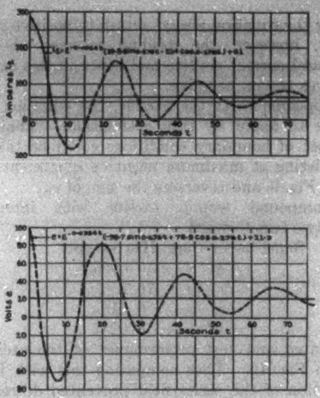

FIG. 14

The alternator field resistance prevented reversal, but permitted the exciting current to decrease to about half the value existing before short circuit.

(d) Shunt exciter with interpoles; brushes one-half bar forward; no external resistance in alternator field circuit.

Data: Same as in IIIa except:

$L_2' = 0.42$
$k_a = 0.00012$
$M = -0.0055$
$e' = 100$
$r_1 = 64.5$

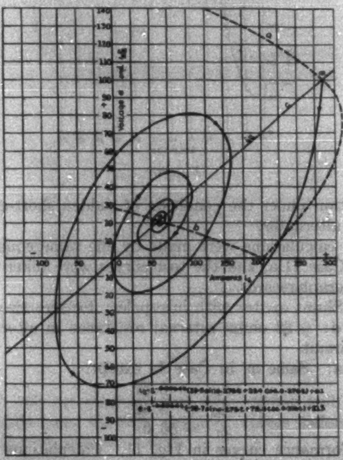

FIG. 15

Fig. 12 shows the exciter to be stable under this condition. That is, with only one-half bar forward shift of brushes from neutral, the droop in the volt-ampere characteristic, as shown in Fig. 4, is not sufficient to cause instability under the conditions of this test.

(e) Shunt exciter with interpoles; brushes two bars forward; automatic voltage regulator; low exciter voltage, to give the least favorable condition for the regulator operation.

No calculations made. Fig. 13 shows the exciter performance under test. The regulator thus prevented decrease in excitation following alternator short-circuit.

Case IV. Switches S_1 and S_2 have been closed and i_1 and i_2 have reached the permanent values i_{11} and i_2'' respectively. The shunt field resistance r_1 is suddenly changed from r_1^0 to r_1'.

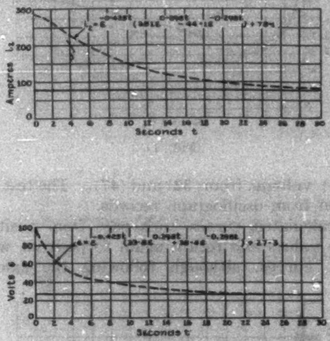

FIG. 16

(a) Shunt exciter with interpoles; brushes two bars forward.

Data: Same as in Case Ia except:

$r_1 = r_1^0 = 51.2$ before
$r_1 = r_1' = 60.0$ after.

Calculated curves are shown in Fig. 14. From the above data γ is imaginary. Hence equations (**42**) and (**46**) were applied for current; (**42**) and (**48**) for voltage. This condition gives very long, low-frequency oscillations, similar to Case Ia. Tests were made, and such oscillations were observed, but were not recorded.

These same calculations are plotted in different form in Fig. 15. Here, the exciter voltage is plotted against the current i_2, both being sine functions of time. This makes it possible to show the transient current and voltage in relation to the volt-ampere characteristics *a* and *b* of the exciter, and *c* of the receiving circuit, *i. e.*, alternator field. The volt-ampere characteristic *a* corresponds to

$$r_1 = r_1^{\circ} = 51.2$$

and b, to

$$r_1 = r_1' = 60.0$$

The curve c corresponds to

$$r_2 = 0.35$$

Before the change the point of operation must be on a and c, thus at m; after, it must ultimately be on b and c, thus at n. The transition is shown by the spiral curve.

(b) compound wound exciter with interpoles; brushes two bars forward.

Data: Same as in Case Ia except:

$$\begin{aligned} M &= +\quad 0.0247 \\ r_1 &= r_1^{\circ} = 76.2 \text{ before} \\ r_1 &= r_1' = 90.0 \text{ after} \\ r_a &= \quad 0.016 \\ k_a &= +\quad 0.00055 \end{aligned}$$

Starting at the same values of exciter voltage and current as in IVa, but now with series field, of course requires higher voltage of r_1.

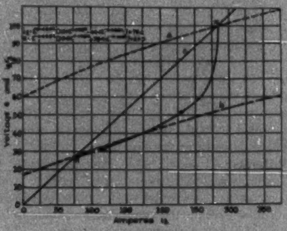

FIG. 17

From this data, γ is real. Hence apply equations (**35**) and (**16**) for current; (**35**) and (**47**) for voltage.

The result is shown in Fig. 16. Thus the series field eliminated the oscillation, giving a gradual decrease of excitation to the new permanent value. As in Case IVa, these data are also plotted in Fig. 17, showing the transient in relation to the volt-ampere characteristics. The curve shows a gradual decrease from the point m on a, to n on b, a and b being the volt-ampere characteristics of the exciter with the series field.

D. NOTATION

A	defined by equation (**10**)
α	exponent, defined by equation (**8**)
a, b, c	integration constants, defined by equation (**38**)
β	coefficient, defined by equation (**9**)
C_1, C_2	integration constants
e	exciter terminal voltage
e'	exciter terminal voltage at no load
e_a	exciter generated voltage
e_0	exciter residual voltage
ϵ	2.718
G	$\frac{d\,i_2}{d\,t}$, given by equation (**30**)
γ	exponent, defined by equation (**14**)
γ'	exponent, defined by equation (**36**)
i_1	exciter shunt field current
i_{11}	particular value of i_1 in Case III
i_{11}'	particular value of i_1, defined by equation (**27**)
i_2	alternator field current
i_2'	particular value of i_2, defined by equation (**25**)
i_2''	particular value of i_2, defined by equation (**33**)
i_a	exciter armature current
i_0	particular value of i_2, defined by equation (**15**)
j	$\sqrt{-1}$
K	total generated armature volts per megaline of magnetic flux per pole
k_1	megalines per pole per shunt field ampere
k_a	megalines per pole per ampere in the armature circuit. It is thus the net result of the armature, interpole and series field magnetomotive forces, and may therefore be either positive or negative. It is positive if magnetizing, *i. e.* if it adds to the shunt field flux; and negative if demagnetizing
L_1	total inductance (henrys) of shunt field circuit
L_2	total inductance (henrys) of alternator field circuit
L_2'	leakage inductance (henrys) between the alternator field and armature circuits, expressed in terms of field circuit
L_a	total inductance (henrys) in armature circuit, including the armature and the series and interpole field windings, if any
M	mutual inductance (henrys) between shunt and series windings. It includes the mutual inductance of any demagnetizing or magnetizing, armature or interpole turns
m_1, m_2	defined by equations (**12**) and (**13**) respectively
r_1	resistance (ohms) of shunt field circuit
r_1°	particular value of r_1 in Case IV
r_1'	particular value of r_1 in Case IV
r_2	resistance (ohms) of alternator field circuit
r_a	ohmic resistance of exciter armature circuit, including series and interpole fields, if any
ϕ	magnetic flux per pole in exciter in megalines
θ	angle whose tangent is $(-b/a)$, equation (**46**)
t	time in seconds

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Discussion

W. A. Hillebrand: A rather startling instance of an oscillation such as Mr. Doherty has just described, came within my observation some three years ago. There was a two-pull electro magnet for a Paulson high-frequency arc converter, the magnet weighing approximately 30 tons, and they had only 5-kilowatts of arc converters at the station. Now the magnet itself was perhaps the most powerful that was ever delivered, and it was excited by a 250-kw., 500-volt d-c. generator, direct connected to a 2400-volt induction motor. Now what happened was that the power went off. The energy stored in the magnetic field was sufficient to stop the motor-generator set, reversing it. This reversal of rotation of the motor generator demagnetized the magnet, magnetizing it in the opposite direction, and again brought the set to rest. That is, there was a highly damped oscillation of very low frequency lasting for a cycle and a half. We ran saturation curves under various conditions, and finally after the last run the current was cut off, and I think some three or four minutes after the machine was completely disconnected, while we were stripping it, we still got an arc, showing the current was still flowing. That is, it took several minutes, due to the very slow decay before the current came to zero.

R. J. C. Wood: This question of exciter instability and the results shown in the paper seem to make a pretty good argument for the individual exciter direct connected on the generator shaft. That is a type of construction to which we are going with our latest large units. When the construction is in that form the exciter can be properly designed to meet the conditions of the generator, and so on, so it will not be working on the low portion of the saturation curve.

While it is not an illustration exactly of exciter instability, yet this calls to my mind the conditions that exist when there is a long transmission line connected to a generator and the generator becomes self-exciting due to the charge on the line. You then get an instability not because the exciter is unstable, but because the whole excitation of the machine is unstable. A certain definite voltage on the transmission line causes a charging current of a certain definite magnitude to flow, and that current leading the voltage excites the armature and the field exactly in an opposite direction to the ordinary demagnetizing effect of a lagging load, consequently if the voltage produced by this exciting current is greater than that necessary to produce the current which caused the excitation, the machine will build up until saturation of the iron causes a balance.

G. F. Brown: Mr. Wood raised the question of the saturation curve. Where a voltage regulator is used, and machines are operated as they are on these large transmission systems, they require a broad range of regulation. A considerable margin in voltage over your operating point of exciter voltage is required, which in general means that you must operate all these machines lower on the saturation curve.

There are some points in this paper on the question of application that bring out the point that more attention should be paid to the application of exciters. For instance, in large steam turbine stations in the east, where there are no extensive lines attached, the results indicate that we should use compound-wound machines. Perhaps I had better carry that a little further. On a system such as you are operating in the West, on long lines, a compound wound exciter has some disadvantages. For instance, the point Mr. Wood spoke of, under conditions of self-excitation it is difficult to carry the regulation of voltage down as low as you would like. In conditions of run-away, it is impossible with the series field on the exciter unless you have a lot of applications in the way of voltage relays and devices for switching resistance into the circuit. It would seem that the simplest application i, e. broad range regulators, shunt-wound exciters, would be preferable for such cases.

R. E. Doherty: I agree with Mr. Wood that for large, important generating units the individual exciter is preferable. There are, of course, the well known points of controversy as to whether a direct-connected exciter is preferable to one driven by other means; not with respect to stability of operation, but to freedom from shut-downs. But, whether direct connected or separately driven, the individual exciter is, in my opinion, preferable.

I agree also with Mr. Brown that there are instances, such as he mentions, where shunt-wound exciters may be preferable to compound-wound. It simply means that in such cases, other considerations, deemed more important, make it necessary to sacrifice the inherently stable feature possessed by the compound exciter.

Electrical Characteristics of Transmission Systems

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In making the electrical calculations for a long transmission line, it is desirable to include the effect of the step-up and step-down transformers and to make a direct calculation for the complete system, without any trial and error procedure. A method for doing this is described for constant-voltage lines, since long, high-power lines, especially those of 220,000 volts, usually require to be operated at constant voltage by means of synchronous condensers. The necessity of using the hyperbolic theory in calculating such lines is pointed out.

THE electrical characteristics of a simple transmission line of uniform design throughout are usually calculated from the resistance, reactance and capacitance of the line. However, the characteristics of the line alone are often not so useful to know as the characteristics of the complete system, including transformers and synchronous condensers, and sometimes with different types of conductors used on different parts of the line. Where synchronous condensers are used, it is usual to assume that they hold the voltage constant at certain points.

In this article is shown a method of calculating the characteristics of a constant-voltage transmission system, including the effect of the transformers, the distributed capacitance of the line, and changes in size and grouping of conductors.

It may be stated as a well-established fact that any transmission line long enough, and with a power load large enough to justify the adoption of 220,000 volts, will require to be operated as a constant-voltage transmission line, using synchronous condensers.

The adoption of 220,000 volts means increased cost of transformers, circuit breakers, line insulators, and towers which must be large enough to provide wide spacing between conductors. It will therefore, be economical to use such a high voltage only for a large block of power transmitted a long distance, and this is found to require a low resistance conductor of large size, approximating one inch in diameter. This large size of conductor is required also in order to avoid trouble from corona, though a large diameter for this purpose may be secured by the expedient of using a large steel core. Now, overhead conductors of very large size have several times as much reactance as resistance, so that the maximum load which may be carried by the line is determined by voltage variation and not by line loss. It is in such cases that synchronous condensers for holding the line voltage constant have been found to be most profitable.

It may also be stated that for any 220,000-volt transmission system, and, indeed, for much less important systems, it is necessary to take accurate account of the distributed capacitance according to the hyperbolic theory, in order to avoid serious errors in the calculated results.

This is very well shown by the transmission line problem given in Fig. 5 of F. G. Baum's paper on "Voltage Regulation and Insulation," JOURNAL of the A. I. E. E., August, 1921, page 648. Mr. Baum used an approximate method of calculation which was not based on the hyperbolic theory. As a result, he obtained a value of 124,000 kv-a. of synchronous condensers for a load of 104,000 kw. As a matter of fact, 82,000 kv-a. of synchronous condensers are required for the line in question at full load, which is the only condition considered in Mr. Baum's paper. Considering both no-load and full-load conditions, the required capacity to maintain constant voltage is 244,000 kv-a., or 235 per cent of the value of the load in kilowatts. There is also a considerable discrepancy in the calculated efficiency due to using the approximate method of calculation. The approximate method gives 71 per cent efficiency, but this should be 77 per cent, according to the data given.

It is doubtless true that synchronous condensers would be required at intervals in order to transmit power 800 miles at 220,000 volts, though possibly not at such close intervals as 150 miles. However, it is necessary to use the hyperbolic theory if even a rough estimate is to be made of the operation of the system or the amount of synchronous condensers required.

A very useful method of determining the size of conductor and the features of loading and controlling a constant-voltage transmission line, is to draw a circle diagram for the line in question. This shows the operation of the synchronous condensers under all conditions of load and it gives the maximum load which can be carried by the line at the voltages considered. The efficiency of transmission and power factor at the generators for various loads may also be conveniently plotted above the diagram. (See Fig. 2.)

The circle diagram is advantageous, first, because it gives results for all loads and not for one or two particular loads only. Second, because it is not a trial and error method but it gives results at once for the definite supply and receiver voltages chosen. In the third place, concentric circles may be drawn with practically no extra calculation whatever, to show the results for different values of the supply voltage E_s. (See Fig. 2.) In the fourth place, it is possible with very little extra work to obtain precise calculated results by means of the calculated data used in making the diagram.

The method of drawing a circle diagram of a constant-voltage transmission line, not including the step-up and step-down transformers, but taking account of the

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distributed capacity according to the hyperbolic theory, has been published by the author in "Constant-Voltage Transmission," pages 78 and 99. The present article gives formulas for drawing the diagram or calculating the results when the transformer resistances and reactances are included in the circuit, the notation used being similar to that in the book referred to. Average values have been taken for the transformer core loss and magnetizing current, and for the condenser loss, and these have been included in the calculation.

A similar method for including the transformer characteristics in the transmission circuit calculation has been worked up by Messrs. R. D. Evans and H. K. Sels and published by them in the *Electric Journal.* A useful reference in connection with this kind of calculation is 'The Calculation of Transmission Line Networks" by Prof. T. R. Rosebrugh, Bulletin No. 1. 1919, of the School of Engineering Research, University of Toronto, which gives the general circuit constants for several lines in parallel, in series-parallel, and with intermediate loads, etc. Such general constants are often applicable in the following circle diagram calculation.

By making allowance for the transformer characteristics, the preliminary calculation is made somewhat longer than for the line alone, but the construction of the diagram itself is not made any more complicated in any way.

Let the constant voltage at the low-tension side of the receiving transformers be E volts to neutral, (equivalent high-tension voltage). See Fig. 1. Let the load current combined with the reactive current from the synchronous condensers be $P + j\,Q$ amperes per conductor, (equivalent high-tension current). Q is a positive quantity when leading and negative when lagging. Let the average loss in the synchronous condensers be represented by the current P_c, in phase with E. Let the core loss and magnetizing current of the receiving transformers be represented by the admittance $G_{tr} + j\,B_{tr}$ at the average operating high-tension voltage. Let the corresponding quantity for the supply transformers be $G_{ts} + j\,B_{ts}$. The core loss current and the magnetizing current of a given transformer are assumed to flow in the primary winding of that transformer and not in the secondary winding. The impedance of the receiving transformers is $R_{tr} + j\,X_{tr}$, and that of the supply transformers is $R_{ts} + j\,X_{ts}$.

The process of calculating the data for the circle diagram consists in starting at the load end, where the voltage E and all other conditions are known except the current $P + j\,Q$. The voltage and current at each part of the system are then calculated, using numerical values of all quantities except that the letters $P + j\,Q$ will always appear. Thus finally the value of E_g will be obtained in terms of P and Q and numerical quantities, See Equation (16) and example I.

In Fig. 1 is indicated a typical constant-voltage transmission line. If the size of conductor, or the spacing, changes at a certain point on the line, the voltage E_{b1} at that point should be marked on the diagram and calculated in the usual way. Voltages in the calculation are considered measured to neutral, and currents are in amperes per conductor. The system is considered to be three-phase.

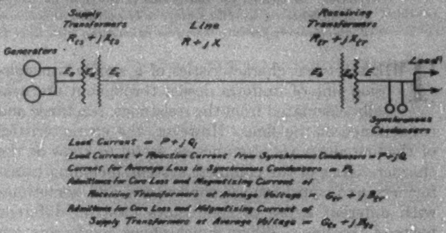
Supply Transformers
$R_{ts}+jX_{ts}$
Line
$R+jX$
Receiving Transformers
$R_{tr}+jX_{tr}$
Generators
E_g
E_d
E_c
E_b
E_a
E
Load
Synchronous Condensers
Load Current = $P+jQ_1$
Load Current + Reactive Current from Synchronous Condensers = $P+jQ$
Current for Average Loss in Synchronous Condensers = P_c
Admittance for Core Loss and Magnetizing Current of Receiving Transformers at Average Voltage = $G_{tr}+jB_{tr}$
Admittance for Core Loss and Magnetizing Current of Supply Transformers at Average Voltage = $G_{ts}+jB_{ts}$

FIG. 1—SCHEME OF CONNECTIONS OF CONSTANT-VOLTAGE TRANSMISSION LINE

Numerical values, except for P and Q, are to be inserted in the following equations;

Current in secondary of receiving transformers

$$I_a = P + j\,Q + P_c \qquad \text{amperes per conductor} \quad (1)$$

Voltage induced in receiving transformers

$$E_a = E + 1/2\, I_a\, (R_{tr} + j\,X_{tr}) \qquad \text{volts to neutral} \quad (2)$$

Current in primary of receiving transformers

$$I_b = I_a + E_a\, (G_{tr} + j\,B_{tr}) \qquad \text{amperes per conductor} \quad (3)$$

Voltage at receiving end of transmission line

$$E_b = E_a + 1/2\, I_b\, (R_{tr} + j\,X_{tr}) \qquad \text{volts to neutral} \quad (4)$$

Voltage at supply end of transmission line

$$E_c = E_b \left(1 + \frac{Y\,Z}{2} + \frac{Y^2\,Z^2}{2 \times 3 \times 4} + \ldots\right) + I_b\, Z \left(1 + \frac{Y\,Z}{2 \times 3} + \frac{Y^2\,Z^2}{2 \times 3 \times 4 \times 5} + \ldots\right) \qquad \text{volts to neutral} \quad (5)$$

Current at supply end of transmission line

$$I_c = I_b \left(1 + \frac{Y\,Z}{2} + \frac{Y^2\,Z^2}{2 \times 3 \times 4} + \ldots\right) + E_b\, Y \left(1 + \frac{Y\,Z}{2 \times 3} + \frac{Y^2\,Z^2}{2 \times 3 \times 4 \times 5} + \ldots\right) \qquad \text{amperes per conductor} \quad (6)$$

The equations for the voltage E_{b1}, and current I_{b1}, etc., at an intermediate point or points where the line characteristics change, are of the same form as (5) and (6).

Note that $Y = G + j\,B$, the admittance of the line, (7)

and $Z = R + j\,X$, the impedance of the line, (8)

The series in $Y\,Z$ are very convergent at commerical frequencies and can be quickly evaluated. It may be noted that

$$1 + \frac{YZ}{2} + \frac{Y^2 Z^2}{2 \times 3 \times 4} + \dots = \cosh \sqrt{YZ} \qquad (9)$$

and
$$1 + \frac{YZ}{2 \times 3} + \frac{Y^2 Z^2}{2 \times 3 \times 4 \times 5} + \dots = \frac{\sinh \sqrt{YZ}}{\sqrt{YZ}} \qquad (10)$$

Current in secondary of supply transformers $= I_e$ (11)

Voltage induced in supply transformers

$$E_d = E_e + 1/2\, I_e\, (R_{ts} + j\, X_{ts})$$

volts to neutral (12)

Current in primary of supply transformers

$$I_d = I_e + E_d\, (G_{ts} + j\, B_{ts})$$

amperes per conductor (13)

Voltage at generator terminals

$$E_s = E_d + 1/2\, I_d\, (R_{ts} + j\, X_{ts})$$

volts to neutral (14)

Current at generator terminals

$C + j\, D = I_d$ amperes per conductor (15)

The voltage and current at the generator terminals may thus be found in terms of P, Q and numerical quantities. It is noteworthy that no trigonometrical calculations are required, but only the multiplying of complex quantitites, for which a slide rule is sufficient. The voltage E remains the reference vector throughout the entire calculation.

Let $E_s = E' + j\, E'' + (P + j\, Q)\, (R' + j\, X')$

volts to neutral (16)

where numerical values have been found for the letters with dashes, from (14).

Equation (16) is of exactly the same form as the equation for a transmission line alone, not including transformers. A circle diagram may therefore be drawn for the complete transmission system indicated in Fig. 1, in which E_s and E are voltages kept constant by means of synchronous condensers. Such a diagram will indicate the kv-a. required from the condensers for any given load.

If, as is sometimes done, the voltage at the supply end is kept constant on the high tension side of the step-up transformers, E_s, the constant supply voltage, would be in the place occupied by E_e, Fig. 1.

From equation (16) the absolute value of the supply voltage E_s may be obtained. Thus,

$$E_s^2 = (E' + P\, R' - Q\, X')^2 + (E'' + P\, X' + Q\, R')^2 \qquad (17)$$

In the case of a constant-voltage line, P and Q are the only variables.

Equation (17) is the equation of a circle. It reduces to

$$\left(P + \frac{E' R' + E'' X'}{R'^2 + X'^2}\right)^2 + \left(Q - \frac{E' X' - E'' R'}{R'^2 + X'^2}\right)^2 - \frac{E_s^2}{R'^2 + X'^2} = 0 \qquad (18)$$

Since P and Q represent currents, equation (18) should be multiplied throughout by

$$\frac{3\, E}{1000} \qquad (19)$$

to give a circle showing the relation between kw. and reactive kv-a. at the receiver end of the constant-voltage line.

The center of the circle is the point (a', b') where

$$a' = -\frac{3\, E}{1000} \; \frac{E' R' + E'' X'}{R'^2 + X'^2} \text{ kw.} \qquad (20)$$

$$b' = +\frac{3\, E}{1000} \; \frac{E' X' - E'' R'}{R'^2 + X'^2} \text{ kv-a.} \qquad (21)$$

The radius is

$$c' = +\frac{3\, E}{1000} \; \frac{E_s}{\sqrt{R'^2 + X'^2}} \text{ kv-a.} \qquad (22)$$

In order to plot the reactive kv-a. required from the synchronous condensers, first draw a straight line at an angle θ below the base line, where $\cos \theta$ is the power factor lagging, of the load. If the power factor is not the same at all loads, the line will not be straight, but will be a curve showing the reactive kv-a. of the load from no load to full load. By means of a pair of dividers add the reactive kv-a. of the load to the corresponding ordinate of the circle, thus plotting the curve of kv-a. required from the synchronous condensers. See Fig. 2.

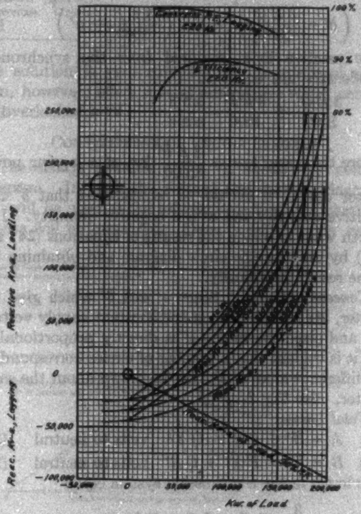

FIG. 2—CIRCLE DIAGRAM FOR 220,000-VOLT, CONSTANT-VOLTAGE TRANSMISSION LINE
(See example 1)

Theoretical Limit of Load, in Kilowatts

Maximum Load $= c' + a'$ kw. **(23)**

This is numerically less than c' since a' is a negative quantity. It may read from the circle diagram as it is the farthest distance to the right reached by the circle.

Calculated Value of Reactive Kv-a. The method described in this article is not necessarily a graphical method. It is possible to calculate the reactive kv-a. directly, which is sometimes desirable in order to obtain a more precise result than that obtained graphically from the diagram. A direct calculation made in this way is less work than a "trial and error" method, which would generally involve calculating the problem more than once.

The value of the reactive kv-a., $\frac{3\,E\,Q}{1000}$, for a given power load $\frac{3E\,P}{1000}$, may be found from the following equation:

$$\left(b' - \frac{3\,E\,Q}{1000}\right)^2 = c' - \left(\frac{3\,E\,P}{1000} - a'\right)^2 \qquad \textbf{(24)}$$

The reactive kv-a. required from the synchronous condensers are equal to

$$\frac{3\,E\,Q}{1000} + \frac{3\,E\,P}{1000}\,\frac{\sin\theta}{\cos\theta} \qquad \text{kv-a.} \qquad \textbf{(25)}$$

where the power load is $\frac{3\,E\,P}{1000}$ kw. at a lagging power factor $\cos\theta$. It should be remembered that b' is a positive quantity and a' is a negative quantity. It is worth while checking the results of equations (**24**) and (**25**) by drawing the circle diagram and obtaining the same results graphically.

Concentric Circles. Since a' and b' which give the center, are independent of the constant supply voltage E_s, and since the radius c' is directly proportional to E_s, it is evident that a number of circles corresponding to different values of E_s may be drawn about the same center. See Fig. 2.

Total Losses.

Let $A = E' + P\,R' - Q\,X'$ volts to neutral **(26)**

and $B = E'' + P\,X' + Q\,R'$ volts to neutral **(27)**

The losses in the transmission system equal

$$\frac{3}{1000}\,(A\,C + B\,D - E\,P) \qquad \text{kw.} \qquad \textbf{(28)}$$

This does not include the generator losses. When the constant voltage E_s is on the high tension side of the step-up transformers the losses in the step-up transformers are not included in expression (**28**). As mentioned before, an average value was assumed for the transformer core loss and the condenser loss. The quantities C and D are found from equation (**15**).

Efficiency of the Transmission System.

$$\text{Efficiency} = \frac{100\,E\,P}{A\,C + B\,D} \qquad \text{per cent} \qquad \textbf{(29)}$$

Kw. at supply end

$$\frac{3}{1000}\,(A\,C + B\,D) \qquad \text{kw.} \qquad \textbf{(30)}$$

Kv-a. at supply end

$$\frac{3\,E_s\,\sqrt{C^2 + D^2}}{1000} \qquad \text{kv-a.} \qquad \textbf{(31)}$$

Power factor at supply end

$$\frac{100\,(A\,C + B\,D)}{E_s\,\sqrt{C^2 + D^2}} \qquad \text{per cent} \qquad \textbf{(32)}$$

The "supply end" is the point where the voltage E_s is kept constant. If this at the generator terminals, as indicated in Fig. 1, expression (**32**) gives the power factor of the generator load. Whether this is leading or lagging must be determined from the following expression:

Reactive kv-a. at supply end

$$\frac{3}{1000}\,(A\,D - B\,C) \qquad \text{kv-a.} \qquad \textbf{(33)}$$

When this quantity is positive the reactive kv-a. and the power factor are leading, and when it is negative, they are lagging.

Example I

Length of line = 200 miles

Frequency = 60 cycles

$R + j\,X = 23.2 + j\,160$ ohms

$Y = +j\,0.00106$ mho

$1 + \frac{Y\,Z}{2} + \ldots = 0.91637 + j\,0.01195$

$1 + \frac{Y\,Z}{2.3} + \ldots = 0.97197 + j\,0.00403$

$P_c = 8.66$ amperes

$R_{tr} + j\,X_{tr} = 1.33 + j\,24.0$ ohms

$G_{tr} + jB_{tr} = 0.000{,}022{,}5 - j\,0.000{,}187{,}5$ mho

$R_{ts} + j\,X_{ts} = 1.61 + j\,29.0$ ohms

$G_{ts} + j\,B_{ts} = 0.000{,}018{,}6 - j\,0.000{,}155{,}0$ mho

$E = 115{,}470$ volts to neutral (line voltage 200,000)

$I_a = P + j\,Q + 8.7$

$E_a = 115{,}480 + j\,100 + (P + j\,Q)\,(0.7 + j\,12.0)$

$I_b = (P + j\,Q)\,(1.002 + j\,0.0002) + 11.3 - j\,21.6$

$E_b = 115{,}740 + j\,220 + (P + j\,Q)\,(1.3 + j\,24.0)$

$E_c = 109{,}680 + j\,2870 + (P + j\,Q)\,(22.9 + j\,178.0)$

$I_c = (P + j\,Q)\,(0.894 + j\,0.013) + 9.9 + j\,99.5$

$E_d = 108{,}240 + j\,3090 + (P + j\,Q)\,(23.4 + j\,191.0)$

$I_d = (P + j\,Q)\,(0.924 + j\,0.013) + 12.4 + j\,82.8$

$E_s = 107{,}050 + j\,3340 + (P + j\,Q)\,(23.9 + j\,204.4)$

$\quad = E' + j\,E'' + (P + j\,Q)\,(R' + j\,X')$

$a' = -\,26{,}600$ kw.

$b' = 178{,}300$ kv-a.

$c' = 213{,}800$ kv-a.

when $E_s = 127{,}020$ volts to neutral (line voltage = 220,000). See Fig. 2, which shows the desired characteristics of the system.

Discussion

For discussion of this paper see page 789.

A Graphic Method for the Exact Solution of Transmission Lines

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Review of the Subject.—*There seems to be a popular superstition among engineers that the voltage and current relations at different points in a transmission line are peculiar and are not governed by Ohms law. This idea is not true. A transmission line is governed by Ohms law just as is any other alternating-current circuit containing resistance inductance and capacity. The only difference from an ordinary circuit is that in a transmission line we must make a correction for the effect of distributed constants.*

If we change the current flowing through a line by an amount I, there will be a voltage change equal to I Z between the two ends of the line. The Z in this case, however, is corrected for the distributed constants of the line. The hyperbolic formula which are so widely coming into use, since Doctor Kennelly has given us tables of complex hyperbolic functions, are merely short methods of determining this Z as well as certain other constants which we must use.

If we start with a certain voltage Eg at the generator; on open circuit, we will have a slightly higher voltage at the receiver, due to the line capacity drawing a leading current through the inductance. As we load the line with a lagging current this voltage rise is counteracted by the impedance drop.

In a similar manner the generator current is equal to the vector sum of the charging current, and the load current which has been multiplied by a constant.

It is possible to express these relations by a vector diagram. Drawing a voltage and current diagram on the same sheet and to suitable scales offers a very convenient method of calculation. From such a diagram it is possible to read directly power and power factor as well as condenser kv-a. necessary for voltage regulation.

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Purpose. (40 w.)
Theory. (200 w.)
Construction of Vector Diagrams. (225 w.)
Current Equation. (400 w.)
Calculations for a Three-Phase Line. (900 w.)
Current Diagram. (200 w.)
Use of the Diagram. (300 w.)
Appendix. (250 w.)
References. (125 w.)

THE purpose of this paper is to describe a quick method of constructing the vector diagram of a power line, from which it will be possible to read directly the voltage, current, power and power factor at either end of the line.

THEORY

The solutions of the equations of voltage and current along a transmission line appear in several forms, of which probably the most useful in power line calculations are the well-known hyberbolic ones

$$E_g = E_r \cosh (n\,\theta) + I_r\, Z_o \sinh (n\,\theta) \qquad (1)$$

$$I_g = I_r \cosh (n\,\theta) + \frac{E_r \sinh (n\,\theta)}{Z_o} \qquad (2)$$

where

E_g = generator voltage E_r = receiver voltage
I_g = generator current I_r = receiver current
$n\,\theta$ is the hyperbolic angle of the line, depending on the length n, the size and configuration of the conductors, and the frequency.
Z_o is the surge impedance of the line, depending on the size and configuration of the conductors and the frequency.

The use of these equations and the technique of hyperbolic functions have been discussed by a number of authors to which a few references are given in the bibliography, so I will not burden this paper with a further discussion. The usual method of solving these equations is an analytical one. This works well enough when the power factor of the load is known, but when condensers are used for voltage regulation, the solution is very complicated. A graphical solution, however, offers several advantages which cannot be overlooked.

CONSTRUCTION OF VECTOR DIAGRAM

The voltage equation. Fig. 1, shows the voltage diagram. In both the voltage and current diagrams E_r will be used as the reference vector from which all angles will be measured. From O draw E_r the reference vector. $E_r \cosh (n\,\theta)$ will be shorter and lead E_r by a small angle. $E_r \cosh (n\,\theta)$ is the generator voltage when the line is on open circuit. The difference between it and E_r is the voltage rise or Ferranti effect in the line.

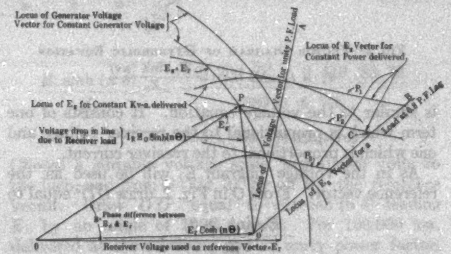
Locus of Generator Voltage Vector for Constant Generator Voltage
Vector for unity P.F. Load
A
Locus of E_g Vector for Constant Power delivered
E_g - E_r
P_1
Locus of E_g for Constant Kv-a. delivered
P
B
Load at 0.8 P.F. Lag
E_g
P_2
Voltage drop in line due to Receiver load
I_R Z_O Sinh(nΘ)
C
Voltage
P_3
Locus of
Locus of E_g Vector for a
Phase difference between E_g & E_r
E_r Cosh (nΘ)
0'
0
Receiver Voltage used as reference Vector-E_r

FIG. 1—VECTOR DIAGRAM OF HYPERBOLIC EQUATION E_r cosh $(n\theta) + I_r\, Z_0$ sinh $(n\theta)$.

Now as we put a load on the end of the line, there will be an impedance drop or rise in the voltage between the receiver and generator ends, depending upon the power

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factor of the load. This is no different from the usual impedance drop in a circuit and is proportional to the current delivered at the receiving end. It is described by the term $I_r Z_o \sinh(n\theta)$ and is represented by the vector $\overline{O'P}$.

The position of the vector $\overline{O'P}$ depends on the character of the load. With a unity power factor load at the receiving end the point P will move along $O'A$. If the amount of power delivered is kept constant while the power factor is varied, P will move along a line perpendicular to $O'A$. With a constant kv-a. load, P will move along the arc of a circle drawn from O' as a center. In order to keep the generator voltage constant as the load on the line is varied, the point P must follow the arc of a circle drawn from O as a center and having a radius equal to E_g.

Current Equation. This current equation:

$$I_s = I_r \cosh(n\theta) + \frac{E_r \sinh(n\theta)}{Z_o}$$

is similar to the voltage equation. It consists of one term which is proportional to the receiver voltage and one which is proportional to the receiver current.

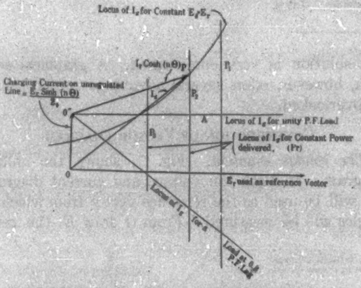
Locus of I_g for Constant E_g/E_r
I_r Cosh (nΘ) P
P_1
Charging Current on unregulated Line = E_r Sinh (nΘ) / Z_o
I_g
P_2
0″
A
Locus of I_g for unity P.F. Load
P_3
Locus of I_g for Constant Power delivered. (Pr)
0
E_r used as reference Vector
Locus of I_g for a Load at 0.8 P.F. Lag

FIG 2—VECTOR DIAGRAM OF HYPERBOLIC EQUATION

$$I_g = I_r \cosh(n\theta) + \frac{E_r \sinh(n\theta)}{Z_o}$$

As in the voltage diagram E_r will be used as the reference vector. From O in Fig. 2, draw $\overline{OO''}$ equal to

$$\frac{E_r \sinh(n\theta)}{Z_o}.$$

This is the charging current taken from the generator when the voltage at the receiving end of the line is E_r. It is necessary to state it in terms of the receiver voltage since all calculations are performed on the assumption of a predetermined receiver voltage. As we load the line at the receiver end by taking a current I_r, a current $I_r \cosh(n\theta)$ will be added to the charging current. This component is almost in phase with the receiver current and a little smaller in magnitude. It is represented by the vector $\overline{O''P}$.

With a unity power factor load, P will be on the line $O''A$. With constant power and varying power factor, P will travel along a line perpendicular to $O''A$. Similarly the locus of P for constant kv-a. load will be a circle drawn from O'' as a center.

Let us examine the voltage and current diagrams together. Any point P on either diagram represents a certain amount of power at a certain power factor which is taken from the line at the receiving end. The vector $\overline{OP}$ on the voltage diagram is equal to the generator voltage necessary to maintain a receiver voltage E_r while P is being delivered. The vector $\overline{OP}$ on the current diagram represents the generator current while P is being delivered. For every point on the voltage diagram, there is a corresponding point on the current diagram.

Let us assume the system to which the line is connected takes a load from the line at 0.80 power factor. Then the locus of point P of the voltage vector E_g will be the line $O'B$ where $AO'B$ is the angle whose cosine equals 0.80; and there will be considerable voltage drop between the generator and receiver for a large amount of power transmitted.

In order to avoid raising the generator voltage to maintain constant receiver voltage, synchronous condensers are used. Their purpose is to draw sufficient reactive current through the line to change the power factor from that of the system load to that necessary for the point P to fall on the constant generator voltage curve. In Fig. 1, the drop caused by this current is the vector $\overline{CP}$. Changing the condenser excitation causes E_g to move along the constant power line P_3.

CALCULATIONS FOR A THREE-PHASE LINE.

The following calculation for a three-phase line is given to illustrate the technique and procedure.

Conductor	Aluminum Steel 605,000 cir. mil aluminum. 78,500 steel Diameter = 0.953 inch
Spacing	Horizontal three conductors 204 inches between conductors.
Line Constants	n = length of line = 241 miles f = frequency = 50 cycles $w = 2\pi f$ = 3.14159 radians per sec. r = resistance = 0.1511 ohm per mile L = inductance = 0.0021015 henry per mile c = capacity = 0.01425×10^{-6} farad per mile g = leakance, so small we will neglect it.

From these constants we will determine the hyperbolic angle θ and the surge impedance Z_o. The mathematics of hyperbolic functions in line calculations has been treated so often before that I will do no more than give the formula. Reference to the theory is given in the bibliography.

$\theta = \sqrt{(r + j\,L\,w) \times (g + j\,c\,w)}$ hyperbolic radians per mile

$Z_o = \sqrt{\dfrac{r + j\,L\,w}{g + j\,c\,w}}$ ohms surge impedance

$L\,\omega = 0.0021015 \times 50 \times 2\,\pi$
$= 0.660205$ ohm per mile

$(r + j\,L\,w) = (0.1511 + j\,0.660205)$
$= 0.6773\ \underline{/77.{}^{\circ}09}$ ohms per mile

$c\,w = 0.01425 \times 10^{-6} \times 50 \times 2\,\pi$
$= 4.4767 \times 10^{-6}$ mho per mile

$(g + j\,c\,w) = (O + j\,4.4767 \times 10^{-6})$
$= 4.4767 \times 10^{-6}\ /\underline{90.{}^{\circ}}$ mho per mile

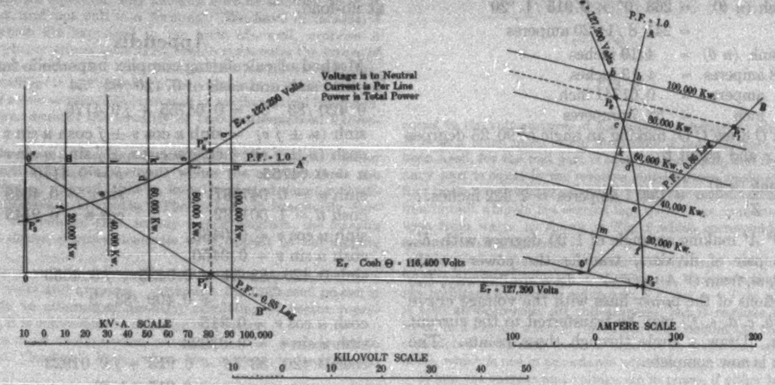
Voltage is to Neutral
Current is Per Line
Power is Total Power
E₈ = 127,200 Volts
P.F. = 1.0
A″
O″
P₂″
P₃″
P₁″
a
b
c
d
e
f
g
h
i
j
k
l
m
20,000 Kw.
40,000 Kw.
60,000 Kw.
80,000 Kw.
100,000 Kw.
O
P.F. = 0.85 Lag
B″
E_r Cosh Θ = 116,400 Volts
E_r = 127,200 Volts
P.F. = 1.0
A
B
P₂
P₁
P₃
O′
P.F. = 0.85 Lag
KV-A. SCALE
10 0 10 20 30 40 50 60 70 80 90 100,000
KILOVOLT SCALE
10 0 10 20 30 40 50
AMPERE SCALE
100 0 100 200

FIG. 3

$\theta = \sqrt{0.6773\ \underline{/77.{}^{\circ}09} \times 4.4767 \times 10^{-6}\ \underline{/90.{}^{\circ}}}$
$= \sqrt{3.0321 \times 10^{-6}\ \underline{/167.{}^{\circ}09}}$
$= 1.7412 \times 10^{-3}\ \underline{/83.{}^{\circ}54}$ hyperbolic radians per mile

$Z_o = \sqrt{\dfrac{0.6773\ \underline{/77.{}^{\circ}09}}{4.4767 \times 10^{-6}\ \underline{/90^{\circ}}}}$
$= \sqrt{0.15125 \times 10^{6}\ \overline{\backslash 12.{}^{\circ}91}}$
$= 389.0\ \overline{\backslash 6.{}^{\circ}45}$ ohms surge impedance.

$n\,\theta = 241 \times 1.7412 \times 10^{-3}\ \underline{/83.{}^{\circ}54}$ hyperbolic radians
$= 0.420\ \underline{/83.{}^{\circ}54}$ hyperbolic radians.

Since $(n\,\theta)$ is a complex hyperbolic angle, tables or charts of complex hyperbolic functions are of great advantage in determining sinh $(n\,\theta)$ and cosh $(n\,\theta.)$ Such charts and tables have been calculated and published by Doctor Kennelly.[1] If no such tables are available, the complex functions can be easily calculated from tables of real circular and hyperbolic functions which are found in every handbook.

$\text{Cosh}\ (n\,\theta) = 0.915\ \underline{/1.{}^{\circ}20}$
$\sinh\ (n\,\theta) = 0.410\ \underline{/83.{}^{\circ}9}$

$Z_o \sinh\ (n\,\theta) = 389.0\ \overline{/6.{}^{\circ}45} \times 0.410\ \underline{/83.{}^{\circ}9}$
$= 159.5\ \underline{/77.45}$ ohms.

It is decided to maintain a voltage between wires of 220,000 volts at the receiving end. This gives the voltage to neutral $E_r = 127{,}200\ \underline{/0^{\circ}}$ volts

$E_r \cosh\ (n\,\theta) = 116{,}400\ \underline{/1.{}^{\circ}20}$ volts

$$\frac{E_r \sinh\ (n\,\theta)}{Z_o} = \frac{127{,}200\ \underline{/0^{\circ}} \times 0.410\ \underline{/83.{}^{\circ}9}}{389.0\ \overline{\backslash 6.{}^{\circ}45}}$$
$= 134.1\ /\underline{90.{}^{\circ}35}$ amperes

Choose a suitable voltage scale, say 10,000 volts to the inch, and from O (Fig. 3) lay off E_r, the reference vector. Draw $\overline{O\,O'}$ equal to E_r cosh $(n\,\theta)$ leading E_r by an angle of 1.20 degrees. For 100,000 kw. delivered at the receiving end at unity power factor, I_r will equal 263. $\underline{/0^{\circ}}$ amperes per phase.

$I_r\,Z_o \sinh\ (n\,\theta) = 263\ \underline{/0^{\circ}} \times 159.5\ \underline{/77.{}^{\circ}45}$
$= 41{,}900\ \underline{/77.{}^{\circ}45}$ volts
$= 4.19\ \underline{/77.45}$ inches

From O' draw $O'\,A$ making an angle of 77.45 deg. with E_r. This is the unity power factor line. Measure up 4.19 inches from O' and through the point draw a line perpendicular to $O'\,A$. This is the 100,000-kw. line. Distances along $O'\,A$ are proportional to the power delivered at the receiver at unity power factor. We can therefore get a power calibration.

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[1] A. E. Kennelly, Tables of Complex hyperbolic and circular functions, Harvard University Press.

A. E. Kennelly, Chart Atlas of complex hyperbolic and circular functions, Harvard University Press.

$$4.19 \text{ inches} = 100{,}000 \text{ kv-a.}$$
$$\text{or } 23{,}820 \text{ kv-a.} = 1 \text{ inch}$$

From O draw an arc the radius of which is equal to the generator voltage it is decided to maintain by means of condensers. This arc will intersect the constant power lines at b, c, d, e, f.

Current Diagram. For convenience in reading, we will construct the current diagram on the same sheet and to the same scale as the voltage diagram. Since $I_r Z_o \sinh(n\,\theta)$ and $I_r \cosh(n\,\theta)$ are both proportional to I_r, if we use the proper scales we can transfer power points from one diagram to the other with a pair of dividers. Such a current scale is one which will make $I_r Z_o \sinh(n\,\theta) = I_r \cosh(n\,\theta)$.

For 100,000 kw. at unity power factor

$$I_r \cosh(n\,\theta) = 263\,\underline{/0^\circ} \times 0.915\,\underline{/1.^\circ 20}$$
$$= 241.8\,\underline{/1.^\circ 20} \text{ amperes}$$
$$I_r Z_o \sinh(n\,\theta) = 4.19 \text{ inches}$$
$$241.8 \text{ amperes} = 4.19 \text{ inches}$$
$$1 \text{ ampere} = 0.01741 \text{ inch}$$
$$1 \text{ inch} = 57.7 \text{ amperes}$$

From O draw $\overline{O\,O''}$ making an angle of 90.35 degrees with E_r and equal to

$$\frac{E_r \sinh(n\,\theta)}{Z_o} = 134.1 \text{ amperes} = 2.322 \text{ inches.}$$

Draw $O''\,A''$ making an angle of 1.20 degrees with E_r. With a pair of dividers, transfer the power points h, j, k, l, m, from $O'\,A$ to $O''\,A''$. In a similar way, the intersections of the power lines with the voltage curve (points b, c, d, e, f,) may be transferred to the current diagram. Draw a circle through these points. The diagram is now complete.

USE OF THE DIAGRAM

It is desired to know the terminal conditions when 90,000 kw. is being delivered at the receiving end at 0.85 power factor. Draw $O'\,B$ the 0.85 power factor line. This is drawn at such an angle that $A\,O'\,B = \cos^{-1} 0.85$. Measure up 90,000 kw. along $O'\,A$ and draw the constant power line through the point. The intersection of the constant power line and the constant power factor line determines the power point P_1. The generator voltage required to deliver this power is the vector $\overline{O\,P_1}$ and is equal to 150,600 volts and leads E_r by 13.5 degrees. To bring the generator voltage down to 127,200 volts will require an amount of condenser capacity equal to $P_1 \,.\, P_2$ or 62,800 kv-a. The generator voltage vector will be $O\,P_2$ and will lead E_r by 18.6 degrees.

Locate P_1'' and P_2'' on the current diagram to correspond to P_1 and P_2 on the voltage diagram. Then $O\,P_1''$ is the generator current when no condensers are used, and is equal to 220.0 amperes. The generator power factor is the cosine of the angle $P_1\,O\,P_1''$. $P_1\,O\,P_1'' = 12.^\circ 3 \cos 12.^\circ 3 = 0.977$.

The total three-phase power delivered by the generator is $3 \times 150{,}600 \times 220.0 \times 0.977 = 97{,}100$ kw. The line loss is equal to $97{,}100 - 90{,}000 = 7100$ kw.

The vector $\overline{O\,P_2''}$ is the current when the generator voltage is regulated to 127,200 volts. It is equal to 275 amperes. The power factor is the cosine of the angle $P_2''\,O\,P_2$. Power factor $= 0.945$.

$$P_g = 3 \times 127{,}200 \times 275 \times 0.945 = 99{,}000 \text{ kw.}$$
$$\text{Line loss} = 99{,}000 - 90{,}000 = 9000 \text{ kw.}$$

To keep the generator voltage constant at no load will require a lagging condenser capacity equal to $O'\,P_3$ or 28,900 kv-a. This is very small when compared with the full load condenser capacity. It would, therefore, be more economical from the point of view of buying condensers to choose a voltage which would require the same condenser capacity at full load as at no-load.

Appendix

Method of calculating complex hyperbolic functions. To find sinh and cosh of $0.420\,\underline{/83.^\circ 54}$

$$0.420\,\underline{/83.^\circ 54} = 0.04755 + j\,0.4170$$
$$\sinh(u \pm j\,v) = \sinh u \cos v \pm j \cosh u \sin v$$
$$\cosh(u \pm j\,v) = \cosh u \cos v \pm j \sinh u \sin v$$
$$u = 0.04755 \qquad v = 0.4170$$
$$\sinh u = 0.047567 \qquad \sin v = 0.4049$$
$$\cosh u = 1.001132 \qquad \cos v = 0.9143$$
$$\sinh u \cos v = 0.0435$$
$$\cosh u \sin v = 0.0450$$
$$\sinh 0.420\,\underline{/83.54} = 0.0435 + j\,0.4050$$
$$= 0.409\,\underline{/83.^\circ 9}$$
$$\cosh u \cos v = 0.915$$
$$\sinh u \sin v = 0.01923$$
$$\cosh 0.420\,\underline{/83.54} = 0.915 + j\,0.01923$$
$$= 0.915\,\underline{/1.^\circ 2}$$

This method of calculation gives a little more accurate result than it is possible to get with the charts or tables.

If, instead of using the hyperbolic functions, it is found more convenient to use the Steinmetz equations:

$$E_g = E_r\,(a_1 - j\,a_2) + I_r\,(b_1 - j\,b_2)$$
$$I_g = E_r\,(d_1 - j\,d_2) + I_r\,(a_1 - j\,a_2)$$

the procedure will be just the same, except that in these equations the phase rotations are reversed.

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This contains an explanation of Vector Arithmetic.

William Nesbit, *Electric Journal*, June, 1920.

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Discussion

DISCUSSION ON "A GRAPHIC METHOD FOR THE EXACT SOLUTION OF TRANSMISSION LINES"

(HOLLADAY)

AND "THE ELECTRICAL CHARACTERISTICS OF TRANSMISSION SYSTEMS" (DWIGHT)

Vancouver, B. C., August 10, 1922

R. J. C. Wood: Again we have an illustration of how, in different parts of the world, and at the same time, the same ideas arise simultaneously. The curves shown in this paper (Dwight) are—I think if you turn the diagram right over, or the wrong way up, according to who is talking about it, that it will be found to be very similar, if not identical with the curves to be shown in the paper by Mr. Holladay. That paper shows a diagram which represents the exact hyperbolic equations.

When it comes to the purity of the English language, doesn't equation simply mean that two things are equal, and if we have an approximate equation, why shouldn't we be satisfied to let it go at that, and not call it a formula. We have equations, I believe, which are expressed in the form of—well, suppose *A* equals *B*, plus or minus something, which represents the errors of observation of something else, I think that is still an equation, without calling it a formula. The dictionary states that a formula is a rule or principle expressed in mathematical language. An equation denotes the equality of two mathematical expressions.

J. R. Dunbar: The diagram in Fig. 2 of Mr. Dwight's paper shows reactive kv-a. in a circuit where the current leads the voltage, plotted upward, that is, kv-a. is plotted counter-clockwise with respect to kilowatts. The A. I. E. E. Standards, Section 3230, recommend that, in any vector diagram, the leading vector be drawn counter-clockwise with respect to the lagging vector.

The above rule is universally followed for vector diagrams involving volts and amperes. Although the apparent power is not strictly an alternating quantity admitting of vector representation, it is convenient to consider it a vector.

It is the usual custom when referring to kv-a. in a circuit to talk about "leading" kv-a. when the current is leading the voltage. If, then, kv-a. is considered as a vector, leading kv-a. must be plotted counter-clockwise from kw. in order to be consistent with Rule 3230. If apparent power is not considered as a vector, there is no justification for drawing any vector diagram of apparent power.

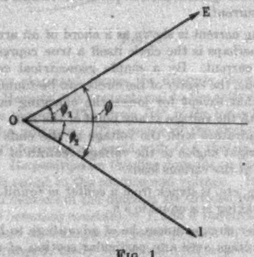

FIG. 1

Section 3238 of the Standards defines volt-amperes as the product of the r. m. s. value of the voltage by the r. m. s. value of the current. If volt-amperes be considered as a vector, it is convenient to have a method of computing the vector value. The expression which at once suggests itself is $\underset{.}{E}\,\underset{.}{I}$, when $\underset{.}{E}$ and $\underset{.}{I}$ are the vector values expressed as complex numbers.

In a case such as is shown in Fig. 1 where $\underset{.}{E} = E\,(\cos\phi_1 + j\sin\phi_1)$ and $\underset{.}{I} = I\,(\cos\phi_2 - j\sin\phi_2)$ the expression $\underset{.}{E}\,\underset{.}{I}$ is very cumbersome and difficult of interpretation, because the real part is not equal to the watts. The use of the numbers conjugate to $\underset{.}{E}$ and $\underset{.}{I}$ simplifies this computation considerably.

Two complex numbers are conjugate to each other, as defined in elementary works on algebra, when they differ in the sign of the imaginary part only.

If the current is multiplied by the conjugate of the voltage, the expression $E\,I\,(\cos\phi_1 - j\sin\phi_1)\,(\cos\phi_2 - j\sin\phi_2)$ is obtained. This reduces to $E\,I\,(\cos(\phi_1+\phi_2) - j\sin(\phi_1+\phi_2)$ or $E\,I\,(\cos\phi - j\sin\phi)$.

This is an expression for volt-amperes, for its effective value is equal to the volt-amperes of the circuit as defined by Rule 3238. It is in a much more useful form than if the conjugate had not been used, for the real part is equal to the watts, and the imaginary part is equal to the reactive volt-amperes, as shown in the foot notes to rules 3242 and 3246. Also the vector volt-amperes, in a circuit wherein the current lags the voltage, is plotted clockwise from watts, as shown in Fig. 2 which corresponds to the assumption made above.

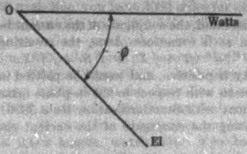

FIG. 2

If instead of the above procedure, the voltage were multiplied by the number conjugate to the current, as is sometimes done, the resultant expression reduces to $E\,I\,(\cos\phi + j\sin\phi)$. This is also an expression for volt-amperes, but it requires that the kv-a. in a circuit wherein the current lags behind the voltage be considered as leading kv-a. in order to be consistent with Rule 3230, which is not in accordance with the usual custom.

When the current and voltage are in phase, if either be multiplied by the number conjugate to the other, it is readily seen that the resultant expression is a real quantity; that is, watts.

It is to be hoped, therefore, that Standardization rules will be added defining volt-amperes as a quantity capable of vector representation for use in transmission line diagrams, etc. and giving rules as to the proper method of plotting volt-amperes.

H. B. Dwight: Mr. Dunbar's demonstration that a transmission line circle diagram should follow Standardization Rule 3230 for vector diagrams, is interesting and convincing. A diagram showing kw. and leading and lagging reactive kv-a. is to all intents and purposes a vector diagram, and Rule 3230 explicitly applies to *any* vector diagram. It would be inconsistent to draw a diagram of a certain shape to express a set of relations between currents in a transmission system, and then draw a diagram of a different shape to express the same set of relations between kv-a. which represent exactly the same currents.

The use of conjugate numbers, which are very advantageous in many calculations, does not require that the above conclusion be changed, but merely that the conjugate of the proper numbers be taken. Where the conjugate of an impedance is required, no difficulty is encountered.

The use of conjugates is both easy and natural. It will be remembered that a complex fraction is multiplied above and below by the conjugate of the denominator, in order to rationalize the denominator. In a somewhat similar way, when multiplying a complex voltage by a complex current, if the conjugate of the voltage is used, the resulting expression can be used to represent the volt-amperes, with the additional advantage that the real part is equal to the watts. It is necessary to use the conjugate of the voltage in order not to conflict with Standardization Rule 3230, but this can easily be done.

While the most usual and general problem is the multiplication of a voltage by a current, the matter is very clearly set forth by an example of a complex value of current $I\,(\cos\theta + j\sin\theta) = Ie^{j\theta}$ and an impedence $R + jX$. The voltage across the impedance is $Ie^{j\theta}\,(R + jX)$, and the conjugate of the voltage is $Ie^{-j\theta}\,(R - jX)$. If now, in accordance with the previous paragraph, the conjugate of the voltage be multiplied by the current, the resulting expression for *v - a.* is $Ie^{j\theta}\,Ie^{j\theta}\,(R - jX) = I^2R - j\,I^2X$. It is seen that the real part is equal to the watts and the unreal part is equal to the reactive volt-amperes, which are negative when lagging, thus agreeing with Standardization Rule 3230.

If, on the other hand, the conjugate of the current be multiplied by the voltage, as is sometimes done, the resulting expression for *v-a* is $Ie^{-j\theta}\,Ie^{j\theta}\,(R + jX) = I^2R + j\,I^2X$. In this, the lagging quantity is positive, and would be plotted in a counterclockwise direction with respect to the in-phase quantity. This is in disagreement with Standardization Rule 3230, and so the procedure of using the conjugate of the current should not be followed.

Since both methods described have been used in publications, it is desirable that a decision be made. A phrase could be inserted in Rule 3230 of the Standardization Rules of the A. I. E. E. stating that it applies also to the diagrams involving volt-amperes.

S. Barfoed: Referring to Mr. Dwight's paper and statement regarding transmission line problem, given in Fig. 5 of F. G. Baum's paper on "Voltage Regulation and Insulation" JOURNAL of the A. I. E. E. August 1921, page 648, it should be understood that all diagrams and computations were made as simple as possible for the sake of explaining the general nature and solution of the long distance high-voltage transmission problem by means of synchronous condensers at the receiving end as well as at intermediate points at nearly uniform intervals along the line. Studies which we have been making seem to indicate that condenser stations should be placed at intervals of about 100 to 150 miles, provided that the voltage is not less than 220,000 volts and that economical powers are transmitted of the order of magnitude of 150,000 to 175,000 kw. per 3-phase circuit. Kelvin's law must here not be forgotten.

If power is transmitted a distance of 300 miles I would by all means advocate any solution which is accurate, but not more so than the nature of the problem demands. A diagram which has been in use in our office for years for solving transmission line problems for lines from 100 to 200 miles in length, is shown in Fig. 1. It is no different from that given by Mr. Holladay and more easily understood by most engineers. The accuracy is all that may be desired for lines of that length.

The basis for the construction of the diagram was given by Mr. Baum 22 years ago (see A. I. E. E. TRANSACTIONS, pp. 412-422, May 1900). I am glad to see that both Mr. Dwight and Mr. Holladay have adopted this same circle diagram, although they arrive at its construction by the use of the functions of the hyperbolic angle. Mr. Holladay's diagram is exactly of the same form as one of several gotten out by me and published in the *Pacific Service Magazine* several years ago. In these diagrams the constants of step-up and step-down transformers were taken account of, as well as the influence of the charging current.

The diagram may be constructed quickly and accurately as follows:—

Direction *O a* is vector of reference. Distance *O a* = 100 per cent = constant and equal generator and receiver voltage for all loads. Swing arc *a f* which is then the locus of end of generator voltage vector for all loads.

At no load the Ferranti effect is represented by the triangle *a b c*, in which *a b* is the resistance pressure and *b c* the reactance pressure caused by the charging current flowing over ½ of line resistance and ½ of line reactance, including transformer, etc. Now load the line with a load of unity power factor, *c d* is then the resistance pressure caused by the power current flowing over all resistance in series and *d e* the reactance pressure caused by the power current flowing over all reactance in series. *e c* is the resultant and is the impedance line for full load with unity power factor of load. The triangle *c d e* is made up of as many triangles as is required to include all pieces of apparatus and the line between the generator and the receiver over which the power current flows in series.

If no attempt were now made to hold the voltage constant, a line drawn from *O* to *e* would represent the generator voltage required at unity power factor of load; at a power factor of 95 per cent it would be represented by a line from *O* to *f'''*; at 85 per cent by *O f'*, and for constant kv-a. of load by *O r*, etc. For other loads than full load the quantities are referred to the respective load lines. By causing a quadrature leading current to flow over the reactances, a voltage drop may be compensated for, and by quadrature lagging currents, voltage rises may be compensated for. A synchronous condenser will perform such service when placed in parallel with the load; that is, it acts as a variable condenser for excitations above normal and as a variable reactor for excitations below normal.

If one were sure of the exact numerical value of the load power factor for any load, then it might be of some value to know with mathematical accuracy the particular quadrature currents needed for each load condition.

A very small change in power factor, however, will demand an enormous change in condenser capacity, by far outstripping any small error in the determination of the Ferranti effect represented by the small triangle *a b c*.

To the left in the figure, the current diagram is drawn so that a good view is had of the manner in which the current and voltage vectors change position with change in load. It is seen how the quadrature currents from the synchronous condenser subtract from or add to the everpresent charging current. At *O l* the quadrature condenser subtracts from the charging current at maximum; then as the load comes on gradually it becomes less until at *p* the condenser is idling, after which, upon further increase in load, the quadrature current reverses and adds itself to the charging current.

The charging current is shown as a chord of an arc of a circle, more proper perhaps is the circle itself a true representation of the charging current. By a simple geometrical construction, which is obvious, the center of the circle can be found, when it is remembered that except for losses the charging current is in quadrature with the voltage at any point of the line. It is therefor also in quadrature with the voltage at the ends of the line, and hence at right angles to the voltage vectors of the receiver and generator at the various loads.

The arc *l n p*, etc. is struck from a center *m* found by locating angle *B* and making *m n* equal to *o b*.

It may, under circumstances, be of advantage to have a drop or a rise in voltage over any particular section of a long line, controlled by condensers at intervals. In such event the diagram at once gives information of what takes place. There may then be a shift to the 110 per cent arc or the 90 per cent arc, or to a curve which would coincide with the 100 per cent arc at no load and with the 110 per cent arc at full load, or vice versa. This is accomplished by adjustment of the potential to the voltage regulator.

The charging current is a function of the impressed voltage. If the voltage is not uniform but changes along the line, the charging current per unit length of line also changes. For a constant voltage system the charging current is therefore constant per unit length of line, and no error is introduced by so considering it.

Ivar Herlitz: The question, so often raised among engineers, whether the hyperbolic theory or some other theory should be used in the calculation of transmission lines seems to me to be rather meaningless. It is established beyond question that the constants in the equations for a uniform transmission line are expressed by hyperbolic functions of certain complex quantities; other expressions for these constants are approximations of the hyperbolic expressions, and it is an easy matter to estimate, for lines of different length, the accuracy obtainable with the various approximate expressions, and then from the demands of the problem decide what method to use. The constants for more general cases, where the transformers are considered together with the line, can be calculated according to Mr. Dwight's paper, or by a similar method described by me in a paper to be published.

The treatment of the equations, after the constants have been determined, depends upon the nature of the problem to be solved. When it is desired to calculate the complete performance of a given line, a circular diagram, for instance of one of the types described in the papers by Dwight and Holladay, may be drawn. In my paper just mentioned I have presented formulas from which the complete performance can be plotted in the form of a few curves giving the loss in active as well as reactive power, and voltage drop for any load condition. For certain other problems I have with advantage used a diagram based on the following principles.

Redrawing Fig. 1 of Mr. Holladay's paper so that the line $O'A$ becomes standard phase, the diagram shown in Fig. 3 is obtained. Here $O'A$ is proportional to the active power, AP to the reactive power. The circle PP' is the locus for P for fixed values of the voltages. The center of the circle always lies on the line OO', forming an angle with $O'A$ that is constant for a given line. Its position on this line depends on the voltages, and the radius is equal to the sending end voltage. If, however, the values of all vectors in the diagram are divided by V_r, the radius of the circle becomes constant = 1, and if the circle is drawn on a separate sheet of transparent paper it may, by means of scales properly arranged, easily be located with respect to a system of coordinate axes to represent any desired case for any line. One diagram can be used for all lines, and it can easily be provided with scales for convenient determination of all desired quantities. The readings have to be multiplied by certain proportionality factors depending on the constants of the line. A similar circle can be drawn representing the conditions at the sending end, and corresponding points on the two circles are found by means of the angular displacement between the voltages, which is equal to the angle $O'OP$ plus a certain fixed angle, as can be seen from Fig. 1 of Mr. Holladay's paper.

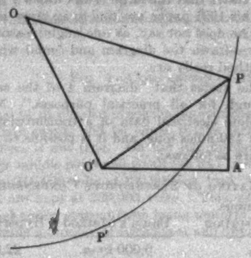

Fig. 3

D. I. Cone: I want to call your attention to the comparison of these two diagrams, one in Mr. Dwight's paper, and the other in Mr. Holladay's paper. You get a pretty full diagram presented by Mr. Holladay and the corresponding one discussed by Mr. Barfoed is the physical picture given, which is more powerfully expressive than when you get away from the physical picture, as it seems to me Mr. Dwight is doing on the diagram itself. That is all right for a man who is continually dealing with the problem but for others the whole picture is wanted.

A word about when to use these approximations. In my own work I am sometimes dealing with 50 cycles, and again with 500 cycles or 26,000 cycles, and I have found that it was very helpful to consider what fraction of a wave length of line they are dealing with, and on open-wire lines the velocity of transmission always works out pretty close to 180,000 miles per second. If you have a 60-cycle line, you have 3000 miles for one wave length, and if you are working on a line 150 miles long, that is one twentieth of a wave line—pretty short; but if you set it now to 600 cycles, the line 150 miles long, it becomes half a wave length, which is a very different proposition. In dealing with short lines (I think we can safely define the short line as on the order of one-twentieth of a wave length) we can feel safe in using the approximation. If your line approaches anything at all to a quarter of a wave length, watch out. You had better then recognize the fact that at this time due to the work of Dr. Kennelly and others the hyperbolic functions are practically as easy to use as any of these approximations.

About the effect of irregularities in the line, a recent interesting case came up in connection with the Portland-San Francisco telephone lines being adapted to the carrier transmission between five and 3000 cycles. A quite serious irregularity was found in the voltage current relations on the Portland end. It was found to be due simply to the fact that the spacing was 30 inches between the wires in the City of Portland instead of 18 inches, as on the rest of the line, due to the municipal requirements for climbing spaces. It made a serious irregularity in the sending end of the voltage-current relation which has to be corrected by special means.

F. G. Baum: (by letter): In a paper giving "Some Constants for Transmission Lines" before the A. I. E. E. in 1900 (See pp. 412-422, Trans. May 18, 1900), I showed a method of calculating transmission lines using complex quantities, which showed for the first time the conditions for any load and any power factor. The error for the loaded and unloaded line was shown to be very small for lines less than 200 miles long. And the only error results from the assumption that the charging current is uniform for each line section.

Now, it is admitted that to transmit power over very long distances we must have synchronous condensers at certain intervals to maintain a *constant voltage system* as shown in my paper on "Voltage Regulation and Insulation for Large-Power Long-Distance Transmission Systems." A. I. E. E., 1921. If we do this then it follows that the charging current is also a constant. And if the charging current is uniform, then there is no need for the hyperbolic calculations.

If we are not to hold the line voltage constant, then I admit we need the hyperbolic method of calculations. But why use a method of calculation for an impractical system?

Diagrams 2 and 3 of my paper referred to are *absolutely* accurate. Diagram 4 is accurate enough for all practical purposes. Diagram 5 was given to show the general problem visually. An error in making the diagram accounts for the discrepancy pointed out by Mr. H. B. Dwight and which I acknowledged to him.

In my method we calculate not a 500 or 1000-mile line but calculate the sections between condensers. The errors resulting could never be measured on the completed line by any instrument used in operating the system. The results are shown visually for all conditions of loading.

H. L. Melvin: We who are actively engaged in transmission line design have our pet way of making calculations, I am sure. Whether we use a simple calculation, a graphical chart or an exact solution, depends entirely upon the problem, and it is really our own good judgment which tells us just which solution to use. Furthermore, I believe most of us know how to use any of the methods which have been devised by the technicians. These methods which we have are really a combination of our own study originality and the ideas of others. Personally I like to use the Perrine-Baum graphical chart simply because it gives you a very nice picture of the actual performance of the transmission line. I simply take a piece of cross-section paper and determine upon the kilowatt scales, use one wire values and make a chart somewhat similar to that devised by Professor Carpenter and presented, I believe, at Los Angeles in 1919. It is a Perrine-Baum chart modified, from which you can get practically all the information you want, voltages, per cent voltage regulation, kilowatts, kilowatt-amperes, power factor and synchronous condenser capacity for power factor correction. On the kv-a. circles the $I^2 R$ transmission line loss can be placed. The point where the loss in the synchronous condenser increases faster than the $I^2 R$ loss in the line decreases can also be determined. That point is approximately the economic or most efficient point at which to operate the transmission line. If you have a problem which requires a more exact solution, the values of resistance and reactance can be modified by the use of hyperbolic functions, and what Dr. Kennelly calls the equivalent values, derived. These values can then be used for making the chart. If you have a still more complicated problem, go through the exact solution. In any event I would make a chart to give a picture of the line, so that good judgment can be used in the design. Pictures mean a great deal to me, if I can see before me just exactly what is going on, I feel that I am better prepared to use good judgment in the proper design. The accuracies of calculation usually exceed by far the original assumptions and necessity in practical application. Temperature change in an ordinary transmission line will introduce more error than the difference between the exact and approximate solution.

Do not misunderstand me, I am not attempting to minimize theory and exact solutions. I have been through them and I feel that I understand them, and they certainly have their value, and unless you do know them you do not know when you can use an approximate solution, or when you have to use an exact solution. The exact solutions are of course absolutely essential on the larger problems. Some of the papers which have come out in recent years are more or less duplicates of papers that have preceded them. I have in mind the sag tension proposition. There were papers after papers on sag tension, different methods of calculation and so on—exact methods and approximate methods. The exact method might tell you to put seven and one-tenth foot sag in the conductor, the approximate solution might say seven feet. If the lineman, gets it within ten per cent, you are lucky.

If you study or go back through the papers that have been written on transmission line regulation and the sag tension problems you will find about every five or six years some one has practically copied an idea of some one before him. We should be careful to give due credit when that is done.

Again I say, practically every one of us have our own pet schemes and could possibly devise some originally and perhaps claim something special for our way of calculating. All these papers are of value if we study them. What we know and use, really are a combination of the other fellow's ideas, coupled with our own.

H. B. Dwight: It has come to be a rule followed by a good many engineers that, in calculating a transmission line at commercial frequencies, if the charging current or capacitance is worth while considering at all, it is worth while calculating its effect by the hyperbolic method. For instance, the old split-condenser method gives rise to an unknown amount of error, and it is better to remove the uncertainty and at the same time effect a standardization of method of calculation, by using the hyperbolic method, which takes practically the same amount of labor as the other.

When a method is advocated which is explicitly not based on the hyperbolic method, it is not sufficient to examine whether its theory appears accurate or nearly accurate, but it is necessary to use the proposed method with a definite example and see if it gives correct results. For this, the criterion by which it must be judged is the hyperbolic method.

Thus, in the last paragraph of Mr. Barfoed's discussion it is stated that "in a constant voltage system the charging current is constant per unit length of line, and no error is introduced by so considering it," but he does not mention any problem which he has worked out as a check of the correctness of his theory for practical purposes, and therefore his statement remains open to doubt until he puts it to the test in the manner described.

So also, referring to the same or a similar method of treating charging current, F. G. Baum says in his discussion that in a constant voltage system the charging current is a constant, "and if the charging current is uniform, then there is no need for the hyperbolic calculations." Now the charging current may be roughly uniform, but the only way to test the above statement is by its results.

Mr. Baum states that the large errors which I pointed out in diagram 5 of his 1921 paper are due to an error in making the diagram, but he does not say, as one might reasonably expect, that he had re-drawn the diagram and found what the errors due to his method really are.

However, he states that "diagram 4 of the same paper is accurate enough for all practical purposes." Now diagram 4 gives complete electrical data of a transmission line of two sections, each 150 miles long, and it is possible to check the results, which are as follows:

RATING OF SYNCHRONOUS CONDENSERS

Synchronous condenser station	Baum's Method	Hyperbolic Method
$S\ C_3$	9,000 kv-a.	22,600 kv-a.
$S\ C_2$	18,000 kv-a.	17,190 kv-a.

If an engineer built a synchronous condenser station for 9000 kv-a. and it was found after load was put on that 22,600 kv-a. of condensers were really required, he would have difficulty in convincing his superiors that his calculations were accurate enough for all practical purposes.

If a method of calculation different from the hyperbolic method is put forward, the advocate of the method should himself first, give clear instructions for using it; second, use it to solve a practical problem; and third, solve the same problem by correct standard methods and show a comparison between his results and the correct results.

C. H. Holladay: There seems to be but two points of discussion, both of which arise whenever a theoretically exact method of calculating a problem is presented. The first is—whether an approximate method is sufficiently exact to use on long power transmission lines. The second, a corrolary to the first, is whether the hyperbolic method of calculation justifies its use.

As an answer to the first question, Fig. 4 shows the hyperbolic diagram of Fig. 3, over which is drawn the ordinary approximate diagram obtained by lumping the capacity at the center of the line. It is evident that the error involved by the approximate method is slight, except in the determination of synchronous condenser capacity. The minimum error which occurs at full load is 8.6 per cent.

It is, therefore, apparent that for lines up to 12,000 cycle miles in length, no serious error is involved in disregarding the effect of disturbed constants. For lines of greater length, however, hyperbolic functions become of increasing importance.

I would like to question the statement made by Mr. Baum, that diagrams two and three, of his paper in the Institute JOURNAL for August, 1921, are *absolutely* correct. As I understand it, Mr. Baum states that if the terminal voltages of a line are kept equal by means of a synchronous condenser, the voltage at intermediate points will be equal to the terminal voltages. This, of course, is not true. On the line discussed above, the voltage at the middle point will go all the way from 224,000 volts at no load, to 219,000 volts at 100,000-kw. load, while the terminal voltages are kept at 220,000 volts. This, of course, would prevent the charging current from being uniform.

In performing a number of both exact and approximate power line calculations, I can see no difference between the two methods, in the labor involved, providing, of course, that tables or charts of hyperbolic functions are available.

There are a number of problems, however, which cannot be handled without hyperbolic functions, and I can see no reason for using two different methods for making a complete set of calculations, when they can be made with the same labor and greater accuracy by using one method throughout.

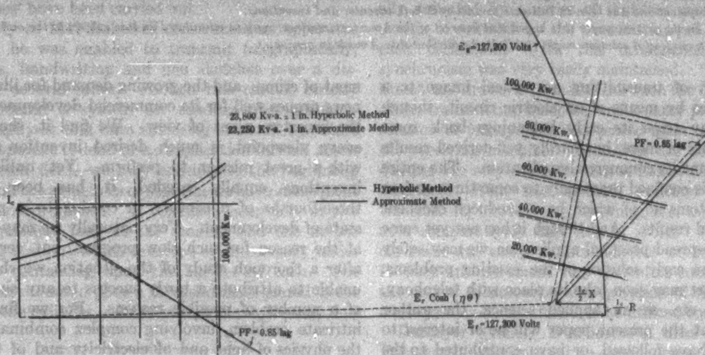
E_s=127,200 Volts
100,000 Kw.
80,000 Kw.
PF = 0.85 lag
60,000 Kw.
40,000 Kw.
20,000 Kw.
23,800 Kv-a. = 1 in. Hyperbolic Method
23,250 Kv-a. = 1 in. Approximate Method
Hyperbolic Method
Approximate Method
I_r
100,000 Kw.
E_r Cosh ($\eta\theta$)
$\frac{1}{2}$ X
$\frac{I_r}{2}$ R
E_r=127,200 Volts
PF = 0.85 lag

FIG. 4—COMPARISON OF HYPERBOLIC AND APPROXIMATE METHODS OF CALCULATION.

In closing, I wish to state that the purpose of my paper has been to outline a systematic method of procedure for the solution of the two fundamental equations of a transmission line. The form of the resultant diagram follows directly from the equations. Mr. Barfoed should feel great satisfaction in its simularity to his diagram, as it shows that, aside from a slight error due to distributed constants, it is fundamentally correct.

Developments in Telephotography

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Transmitting photographs, drawings, maps, etc., by wire or wireless is a problem to which a solution is near at hand, and the present paper is given anticipating the addition of this to our already long list of applied sciences. A brief history is given of the early beginnings, and some of the modern methods discussed; among the latter being Korn's and Belin's. The Leishman systems are discussed at length because the author has been particularly interested in their development and has been in intimate contact with both inventor and inventions.

In the present paper it is hoped that interest of the American engineer may be stimulated in this subject to the end that a successful solution might rightfully be attributed to American genius.

THE art of transmitting an optical image to a distance by means of an electric circuit, though we may trace its early beginnings back some seventy years or more, has hardly yet derived results which warrant its commercial application. The entire field today is confined practically to some three or four distinct systems all of which have produced excellent experimental results. And though it has not yet come to any widespread practical application, we may safely anticipate an early solution of the existing problems. Since this art may soon take its place with telephony, telegraphy, etc. as an applied science, the author believes that the present paper will be of interest to those who have followed, or have contributed to the development of this art, and in the following text will endeavor to describe briefly its history and outline briefly the fundamental principles of each important development. The Leishman Code System will be dwelt upon at greater length because of the more general use it has come into in America.

As stated in the preceding paragraph, *i. e.* the art of transmitting an optical image, the subject divides itself into two general heads; the first, of which may be termed television. This indicates the operation of reproducing upon the apparatus of the receiving station an animate object or image coming within the focus of the transmitting apparatus. Under the second head, which may be generally termed telephotography, and which consists in the reproduction upon receiving apparatus, of an ordinary or especially prepared photograph sent out as electrical impulses or suitable signals from the transmitting station. Though several, including Rignoux, Fournier, and A. Campbell Swinton, have suggested possible solutions the former remains as yet entirely chimerical, and in this paper discussion will be confined solely to the development of the telegraphic transmission of photographs.

The field for application of a system for telegraphing pictures economically is fairly obvious. Its use in warfare, in the speedy transmission of photos, maps, etc. should insure its early adoption by governments; the dispatch with which photographs and finger prints of wanted criminals could be transmitted to all the haunts of civilization would make it an invaluable instrument in the hands of the police in the discouragement of crime; and the growing demand for illustrated news argues well for its commercial development from the investors point of view. We find it, then, from every viewpoint, a much desired invention and one with a great mission to perform. Yet unlike other inventions equally needed, it has been nearly three-fourths of a century in coming to a practical state of development. Very naturally we may wonder at the reason for such slow progress, but very likely after a thorough study of the situation we should be unable to attribute a tardy success to any single one of a number of possible reasons. For we find it an intricate problem, involving complex combinations of the physics of light and of electricity and of the mechanics of motion, etc., and of peculiar properties of elements, compounds and substances which have differed widely from time to time as various investigators have attacked the problem. The chief difficulties that have been encountered by such investigators may be brought out in the following brief description of their individual processes and apparata, and thereafter we may draw conclusions as to their bearing upon the development of the science. From this, also, we may derive an adequate idea of the intrinsic value of the work of early experimenters, as their principles may affect or facilitate the work of subsequent investigators.

In ordinary telegraphy we find it quite impossible to transmit simultaneously the entire contents of a printed page. But by a simple process of splitting it up, first into lines then each line into the words that compose it and further, each word into its constituent letters, we may, by means of suitable signals, and by transmitting one letter at a time, reproduce the entire contents of the printed page to a distant station. The process in telegraphing a photographic image is fundamentally the same. Only one minute portion of the composite photograph can be transmitted at a given instant. These minute portions are arranged mechanically into lines and are read by suitable mechanical means. The apparatus therefore must necessarily consist of, first, a means for dividing the photograph into extremely small component parts; second, a means for interpreting the varying degrees of shading of each component part into varying intensities of electric current; third, a means whereby the variation in the electric current can again be interpreted at the receiving station into light and shade variation corresponding both in

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intensity and in relative position with that of the original photograph. In practise, the third fundamental involves a fourth, that of maintaining exact synchronism in the mechanical motion of the sending and receiving apparatus. Having in mind these fundamental requirements which are common to all methods, we may proceed in a description of the varying ways in which they have been carried out.

As early as 1847 Bakewell constructed an apparatus whereby he was enabled to transmit telegraphically, drawings, handwriting and pen sketches over a distance of several miles. Though this cannot strictly be considered a system for sending photographs—photography at that date not being in a sufficient state of development to lend of its application in such a new and untried field—we may consider it the beginning, since upon the principles of this scheme have subsequent experimenters worked. It consisted essentially of two metal cylinders (one at the sending and one at the receiving station) which revolved synchronously under a stylus contacting upon the surface of each. The stylus was mounted upon a threaded shaft geared to the shaft of the cylinder. In operation the stylus was thus caused to move laterally as the cylinder revolved and to trace a spiral path upon its surface. The subject sketch drawn in insulating ink upon a sheet of tinfoil was mounted upon the first cylinder. A sheet of chemically prepared paper was mounted on the second. The circuit was completed as in Fig. 1. With the current interrupted by the passage of a line of the insulating ink under the stylus, the electrolytic action of the current upon the paper at the receiving station receives a corresponding interruption. With the cylinders in perfect synchronism and the stylus having traversed the entire length of its screw shaft, the lines constituting the original drawing are reproduced upon the chemically prepared paper at the receiving end. To maintain synchronism a series of impulses was transmitted at regular intervals which electromagnetically actuated the clockwork which furnished the motive power for the apparatus. The difficulties in maintaining synchronism, distortion caused by the capacity and inductance of long cables, and other difficulties encountered caused an early abandonment of the scheme.

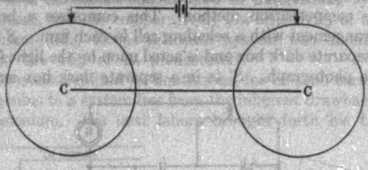

Fig. 1

For many years thereafter no noteworthy results were obtained although several schemes were suggested. In 1859, an Italian priest, Abbe Casseli, had a model of his famous pan telegraph built. Casseli's apparatus, which was both original and ingenious, consisted of a swinging pendulum to which was fastened an arm carrying the stylus. The stylus was caused to trace a line over the surface of a plate which was shifted laterally the width of one line with each oscillation of the pendulum. The receiving pendulum was electrically actuated by a series of impulses caused by the closing of contacts by the transmitting pendulum with each oscillation. With this arrangement absolute synchronism was very easily maintained. The subject sketch was drawn with shellac ink upon the copper plate of the transmitting machine, and a paper prepared in a solution of ferricyanide was placed upon the plate of the receiving machine. Thereafter the actual reproduction was very similar to that of Bakewell, previously described. With this method, excellent results in transmitting handwriting, drawings, etc. were obtained at a comparatively high rate of speed. Perfect synchronism was easily maintained, but we find the field for such an instrument very limited as compared with the cost of construction and operation of stations, and consequently it, too, failed to be utilized commercially.

DeMeyer (1869), D'Arlincourt, Gras and other Frenchmen experimented on similar lines, but with no noteworthy results. In a process suggested by Amstutz we find probably the first concerted attempt to telegraph a photograph. In his process the photographic negative is printed upon a gelatinous prepared paper rendered light sensitive by the addition of bichromate of soda. The emulsion properly prepared has the property of becoming soluble in warm water after exposure to actinic light. The paper prepared with a thick coating of the emulsion is printed in the regular manner and further developed in warm water. The positive thus prepared will have an irregular surface representing the high lights by depressions or hollows and the shadows by hills or prominences. This positive replaced the tinfoil of Bakewell's process upon the transmitting cylinder. A stylus actuated a sort of microphone over its surface with the result that the current in the telegraphic circuit, instead of being periodically interrupted, was caused to vary in its strength, representing a light portion by a weak current and a dark portion by a strong current, since the diaphragm, while the stylus is passing over a prominence, is caused to compress the carbon grains, thus decreasing their resistance. The current in the line will then be theoretically proportionate to the shading of the original photograph at the point touched at any instant by the stylus. To translate such current variations into the black and white of a photograph, Amstutz proposed to use the received current in the direct engravure of a single-line half-tone. To accomplish this, the received current was to regulate, by means of electromagnets, the cutting depth of a *V*-shaped stylus upon a copper plate wound around the receiving cylinder.

Quite obviously such a receiving apparatus is out of the question, since a current strong enough to perform so much work would necessitate a voltage for its transmission quite beyond the capacity of any transmitting device that could possibly be constructed. Thus, through lack of a receiving device, Amstutz failed. His transmitting device was later, however, to figure in the more or less successful scheme of Belin, which will be described in its due order.

In 1873, while conducting some experiments in which selenium was used as a resistance, Willoughby Smith was annoyed by the peculiar instability of his resistance and upon investigation found that selenium possessed the peculiar property of varying its electrical conductivity with the intensity of the light to which it was exposed. With the announcement of this discovery, several attempts were made to utilize these properties in various ways. Notable among these may be mentioned the cell constructed by Prof. Bell which played the principal rôle in the operation of his famous photophone. It was Shelford Bidwell who first suggested its use in the problem of phototelegraphy. He conducted some very interesting experiments in thus applying it, as did also Perry and Ayrton.

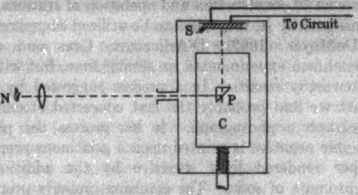

FIG. 2

It remained, however, for Prof. Korn[1] of Munich actually to transmit and receive the first photograph by this means (probably the first to telegraph photographs by any means). His fundamental apparatus is depicted in Fig. 2, where C is a glass cylinder rotating upon a threaded shaft within a dark box and upon which is mounted the subject photograph printed on a transparent celluloid film. The prism P is so placed within the cylinder as to reflect the Nernst beam, which is focused through an aperture in the dark box, upon the selenium cell S, situated at one end of the box. Thus, having passed through the film, the light received by the selenium cell will obviously be a function of density variations in the photographic film as the cylinder rotates and moves laterally. And since the conductivity of the cell is functional with the light which acts upon it, the current in the telegraphic circuit will be at a given instant, directly proportional to the density of the silver deposit upon the film at the particular point through which the light beam instantaneously passes.

Theoretically, such a process encounters no difficulties. In practise, however, the characteristic recovery lag of selenium must be dealt with. If an abscissa represents the time and an ordinate the current, then the conductivity in a cell suddenly exposed to a light of given intensity for a time $L\,O$, may be represented by the curve in Fig. 3. Grantham[2] found by experiment that the resistance actually increased for an instant on exposure. Characteristic lag may be great enough in some instances to last over a period of several seconds, depending upon the purity of the selenium used, upon the construction of the cell, and in a measure upon the temperature under which the cell may be functioning, since its maximum sensitivity has been found to be at 0 deg. cent. Thus it will be seen that with the cylinder rotating at its lowest possible practiable speed, the detail of the original photograph will be lost to such an extent as to give an unrecognizable reproduction at the receiving station. Korn overcame this objectionable feature to a great extent by means of his compensation method. This comprises a bridge arrangement with a selenium cell in each arm. S is in a separate dark box and is acted upon by the light from the photograph. S' is in a separate dark box and is acted upon by the light from aNernst lamp. The Nernst beam is intercepted by a shutter electrically operated by the galvanometer G of a modified Einthoven type. With the passage of current in the circuit, the silver wire bearing the shutter is displaced, permitting a portion of the Nernst beam to fall upon S. With this arrangement Korn claims to have improved the sensitivity of the selenium circuit and to

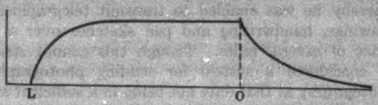

FIG. 3

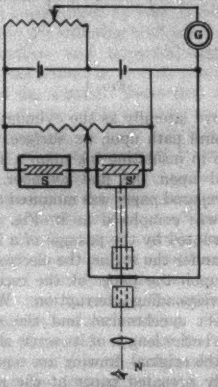

FIG. 4

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[1] T. T. Bakers "Telegraphic Transmission of Photographs."

[2] Grantham, *Physical Review.*

have obtained an effect represented by the curve in Fig. 5. At the receiving end, the Nernst beam was focused upon a sensitized paper. Here again the beam was intercepted by the electrically operated shutter. The displacement of the silver wire bearing the shutter in the galvanometer field is theoretically proportional to the current which flows through it. Thus the light which falls upon the sentitized paper on the receiving cylinder will be proportional to the current in the circuit. To maintain synchronism, an impulse each revolution caused both machines to stop and reset to a predetermined starting point. With this apparatus Korn created considerable interest and its application in the journalistic field was attempted in several of the larger cities of Europe. In the extreme delicacy of the mechanism is found probably its greatest fault. Then, too, with difficulties encountered in maintaining synchronism, and the comparatively low sensitivity of the selenium cells, Korns selenium system was doomed to go the way of its predecessors.

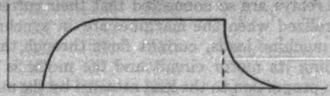
FIG. 5

Korn also realized its limitations, for he soon turned his genius to a system free from the inherent drawbacks of selenium. His next labors brought forth his telautograph. This consisted essentially of a combination of a metal drum and the use of his galvanometer receiving machine.

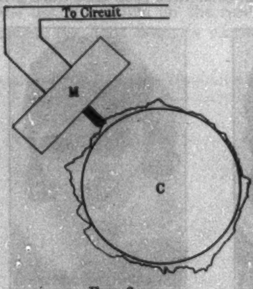

FIG. 6A

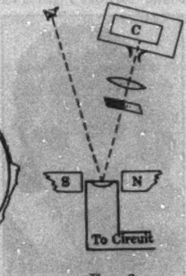

FIG. 6B

Of late M. Edouard Belin has come into the limelight of the telephotographic field and has created considerable interest in his telesteriograph, which he very recently brought to America to demonstrate. So much has been written in the daily press, in the technical and semitechnical periodicals of the country of M. Belin's apparatus, that its description must still be fresh in the minds of those to whose attention the present paper may come. It will be necessary here, then, only briefly to review the elemental principles involved in his apparatus.

As has been indicated above, Belin's process for transmitting utilizes the "relief" photograph as developed by Amstutz, and the sending apparatus is essentially the same as that above described. The scheme is depicted in Fig. 6A. At the receiving end, a Duddell type oscillograph is caused to reflect a beam of actinic light (the angle of incidence being proportional to the current in the galvanometric circuit) over a graduated screen containing, to all practical purposes, all the light variations from transparency to opacity (Fig. 6B). The light, thus varied in its intensity from passage through the screen, is focussed by means of a suitable lens through a small aperture in a dark box in which the cylinder carrying a sensitized paper or films revolves and moves latterly upon a threaded shaft. With the passage of a prominence under the stylus at the transmitting cylinder, the mirror of the oscillograph will be caused to reflect the light beam to the transparent end of the screen, and to the dark end with the passage of a depression under the transmitting stylus. Under development, the sensitized paper or film will represent a faithful reproduction of the original, providing of course that absolute synchronism be maintained between the sending and receiving machines. Some excellent results have been obtained with these instruments and we may hope much from M. Belin's scheme. The French government has been experimenting recently and it is generally understood that some unannounced developments have been made. In warfare, in the criminalistic field and similar applications, its utility seems practicable in the present state of development. In the journalistic field, however, the expenses which its operation entails in the sending of a single photograph make its practical application necessarily very limited.

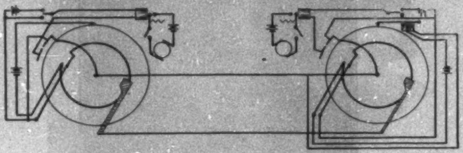
FIG. 7

Possibly the only systems for telegraphing pictures that have been developed in America and that have attained any notable success in the commercial field are those of L. J. Leishman. The first of his two systems was brought into experimental use by the government during the recent war.

His first system, called "screen process" because the preparation of the subject photograph is similar to the process used in preparing newspaper half tones, is meritorious in that it has done much to eliminate complex and complicated apparatus of previous methods. In this method the subject photograph is printed through fine mesh screen, (the purpose of which is to separate the picture into its minute component parts) upon a copper plate coated with a solution of glue and bichromate of ammonia. The positive is developed in warm water and the glue solution is washed away in proportion to the light having acted upon it. The developed positive presents a surface of dots of varying sizes, areas of small or no dots representing the high lights and vice versa. For half tone work the plate of course much be etched which changes the plate again into a negative for printing purposes. With the glue only on the plate however, it represents a positive and it is in this state that it is used for picture telegraphy. The plate is formed into a cylinder and slipped on to the cylinder of the sending machine where a stylus traveling upon its surface and closing the telegraphic circuit, sends out electric impulses varying in length as to the distance between dots. Here we are brought face to face with a reincarnation of Bakewell's metal cylinder having on its surface drawings and writings done in insulating ink and rotating under the contacting stylus, and we may be struck with thought that it isnt such a very far cry from those early attempts of 1847 to the present-day attempts to solve the same problem. The similarity in the two methods ceases, however, with the sending cylinder and the contacting stylus. At the receiving station the impulses as sent by the sending machine are interpreted into the various tones of the original photograph by a means as simple as it is ingenious. The current in the telegraphic circuit passes through two electromagnets actuating an armature bearing a sapphire stylus at its end. Fig. 7. As the impulses from the sending apparatus pass through the electromagnets the stylus is brought to bear upon the receiving cylinder which has around it an ordinary piece of white paper over which has been placed a sheet of carbon paper. With each impulse then, a mark is made on the white paper and as the cylinder revolves synchronously with the sending cylinder the photograph is gradually built up. Fig. 8 represents a photograph received by this method.

FIG. 8—PHOTOGRAPH OF THE MAYOR OF LOS ANGELES AS RECEIVED BY TELEGRAPH

In this system a novel and superior method of synchronizing is used. Korn, Belin and others have synchronized by momentarily stopping one or both of the revolving cylinders. In the newly developed method both cylinders are permitted to revolve continuously. This is accomplished by means of the relays controlling the motor circuit. Batteries actuating the relays are so connected that their current flow is neutralized when the machines are in synchronism. If one machine leads, current flows through the relay controlling its motor circuit and the motor is slowed down in proportion to the lead attained by the machine. It will readily be seen that this is a factor toward faster transmission, and very nearly absolute synchronism is maintained.

Interruptions to the circuit take place at an average speed of 250 times per second; a fact that renders its use on ordinary telegraph lines impossible, since the relays in general use are of a low-speed type. This objection may of course be overcome by vacuum tube relays. Mr. Leishman, however, unsatisfied with this, has turned his genius to what promises to be a long step forward for this science.

In the new process, Leishman utilizes the photoelectric cell in place of selenium, as used by Korn, in surmounting the inherent difficulties that limit its application. Selenium cells have been used during the last ten years in astronomical measurement of ight from stars and planets, but it has been discarded in this work owing to the time necessary for recuperation after exposure and to its susceptibility to climatic influences. Highly satisfactory, in fact we might say perfect, results have been obtained in this work in recent years by the use of the gas photo-electric cell as developed by Kunz. This cell recuperates instantaneously, is not susceptible to climatic conditions and

FIG. 8A—FROM AN ACTUAL PHOTOGRAPH WHICH IS TO BE SENT OVER THE WIRES

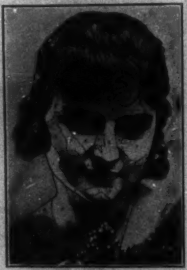

FIG. 8B—PHOTOGRAPH WITH FEATURES OUTLINED AND SHADOWS DIVIDED INTO FIVE DEGREES OF SHADE

has the light sensitiveness of the human eye. With this system, a film on a rotating glass cylinder is used.

For receiving a picture transmitted by this process, Leishman has used a means that will entirely eliminate gravity, friction and mechanical inertia, factors which tend materially to limit the speed of transmission. An electromagnet carrying the current of the telegraphic circuit is caused to rotate in the plane of a polarized beam of light. The degree of rotation is a function of the current in the circuit and the intensity of the light passing the second Nichol prism will depend on the degree of rotation. This method for varying the intensity of the light beam was first suggested by Rignoux and Fournier. This method necessitates the use of the film on the receiving cylinder through which the light beam is carried. This method produces a pure half-tone picture upon the receiving film.

```
LVGIS   MBGWQ   MJIJQ   MTITQ
QIJBQ   QUJDQ   SDIKQ   SQISQ
TEIBQ   TGGQQ   TMFQQ   TSBUA
TDEKA   SMEUQ   QXEMQ   QJEQQ
MYEQQ   MJEKA   MEEIQ   MDETQ
MEFWQ   LVGIQ   LMGKQ   LIGMQ
KVFWQ   KTFTQ   LDFBQ   LAEWQ
LJEGQ   LQDQQ   LUBWQ   MQAVQ
SAAMQ   SKAMQ   TDAVQ   TLBIQ
TUBTQ   TXBVQ   TVDAA   TXDDQ
UADMQ   UAEIQ   TWELA   UBETQ
TXBFQ   TUFQQ   TVFVQ   TUGAQ
TWGMQ   UAGXQ   TSIGQ   TGIFQ
MQFEE   QFFEQ   QMFIQ   QSFMG
QSFAQ   QBEWA   QAEVA   MMEVQ
QAFDM   QJFDM   MTFFE   QBFFQ
QMFLQ   QGFLQ   MXFJQ   MTFFD
QAFIQ   QEFKQ   QGFJQ   QIFGK
QBFIQ   QFFJQ   QFFIQ   QEFFM
QFFGV   QJFIS   QKFKA   QFFLE
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FIG. 8C—THIS IS PART OF THE PHOTOGRAM OR CODE TELEGRAPHIC MESSAGE—THE FORM IN WHICH THE PICTURE IS FLASHED OVER THE WIRES.

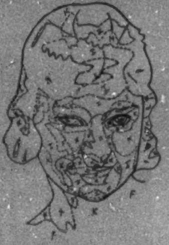

FIG. 8D—THIS IS THE COMPLETE OUTLINE OBTAINED FROM THE CODE, WITH PROPER SHADE LETTERS WITHIN ENCLOSURES.

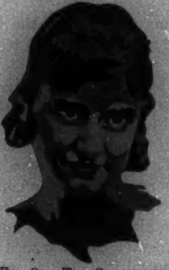

FIG. 8E—THIS SHOWS THE SHADOWS ROUGHLY BLOCKED OUT—POSTER EFFECT

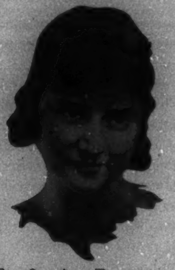

FIG. 8F—AND THIS IS FROM THE FINISHED PICTURE READY FOR PUBLICATION. COMPARE A WITH F

We have seen that picture transmission consists essentially in building up a photograph at the receiving station by placing correctly component parts of the original and by giving each the proper degree of shading. Thus far the systems we have studied have accomplished this by mechanical means only and only a minute portion is transmitted at any instant. In a code system developed by Lieshman we find a deviation from previous practises and though it involves no new application of pure or applied science we may find it of interest in that it is novel and ingenious and has possibly found a wider commercial use than any other process thus far brought out. In this system a photograph is first split up into component parts; this first step differing from previous methods in that large areas comprising one single shade throughout comprise these parts. In Fig. 8B this first step is illustrated.

Being arranged primarily for rapid distribution of current photographs and illustrations for newspaper work this new system concerns itself with only five gradations of shade, further gradations being unnecessary from the fact that only that number appear in the ordinary 60-screen newspaper cut. Each shade may be designated by a letter. In practise *X* indicates white; *F* light grey; *I* medium grey; *K* dark grey; and *M* indicates black. For outlining the areas of one solid shade a continuous line is used when its borders are abrupt and distinct, and a dotted line when two degrees of shade blend. After the picture has been divided in this way it is ready for the coding process. The apparatus consists of a drawing board with a scale across the top denoting the abscissa and an ordinary *T* square with a similar scale along its edges marking off the ordinates, (Fig. 9). The scale is divided into 18 prime divisions and each prime division into 18 subdivisions. For designating these divisions, letters are used instead of numbers for two reasons; first, there are nine digits, which with the cypher, make only 10 possible characters that can be used, while the alphabet

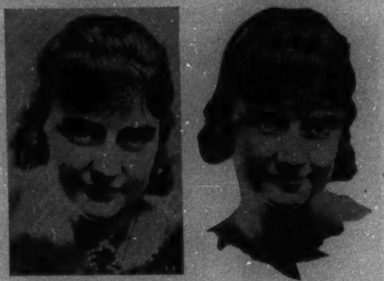

FIG. 8G

The code system was perfected with the needs of a newspaper in mind. A newspaper uses 60 line screen in making its cuts, and therefore neither the original or reproduction would have the clearness or detail shown in these cuts of 100 line screen. The fine screen was used here to make them look as near like the actual pictures as possible, but on account of the detail shown by the fine screen the original and reproduction—A and F—do not look as much alike as they would if printed in a newspaper.

Not only is this due to the screen itself, but to the fact that detail that will not show clearly in a newspaper cut is *purposely* eliminated, as it is foolish to unnecessarily lengthen a photogram to include details that will not produce in a newspaper picture even if the original itself were used. To show that the code system more nearly meets newspaper needs than the previous cuts would indicate, A and F are herewith reproduced as they would appear in a newspaper—in 60 line screen.

affords 26. With letters, therefore, any division and subdivision may be designated by only two characters; second, telegraph companies send five letters in code as one work but for numbers each digit is charged for at the word rate. Since in the scale designed only 18 letters are necessary, those most easily confused in telegraphing are omitted.

With the coding board any determined point on a picture, as fixed by a first coding board, may be accurately placed, relative to other points, by a second.

This is very similar to the familiar way of locating towns and cities on maps where longitude may be indicated by figures and the latitude by letters or vice versa. This for instance, were it desired to locate the town of Podunk in a certain map we find in the key opposite the name of Podunk the characters *R*-6. By this we know that the town is in proximity of the point where longitude 6 intersects latitude *R*.

Obviously in picture transmission utmost accuracy is necessary in properly fixing points and it is therefore necessary to use an infinitely great number of ordinates and abscissas. It follows therefore, that more characters are required to express the exact location of points. It is accomplished by using four letters; the first indicates the prime division on the vertical scale and the second the particular ordinate coming within that division. The third tells which of the prime divisions on the horizontal scale contains the abscissas indicated by the fourth letter. As an instance, *L G V I* indicates the co-ordinate of ordinate *G* in prime division *L* on the vertical scale and abscissa *I* in prime division *V* on the horizontal scale.

The lines circumscribing the various shades are divided having in mind the following two geometrical propositions; first, that two points determine a straight line and, second, that three points determine a circle. In coding a straight line the *T*-square is placed with the scale edge of the *T*-square on the first point. Both scales are then read and the *T*-square placed on the second point and scales read.

Telegraph rules permit five letters to a word in code messages and four are used in locating each point along a line. The remaining letter is used to indicate the various processes to the receiving operator; thus:

Letter *S* indicates beginning of a line
" *D* " end of line
" *A* " end of straight line
" *Q* " cusp
" *W* " end of straight dotted lines } shades
" *U* " cusp dotted } to blend
" *X* " white
" *F* " light grey
" *I* " medium grey
" *K* " dark grey
" *M* " black

Letters indicating shading are given when the circumscribing line is completed, *i. e.* brought back to the point of beginning.

SECTION
BORDER LINE

FIG. 9—CODING BOARD

A finished picture is shown in the illustration, Fig. 10. This was reproduced from the code by an operator who had never seen the original. With this system hundreds of photographs are being sent through the Leishman Telegraph Picture Service Company to progressive newspapers in all parts of the country and though its scope is necessarily limited, due to an inability to code and reproduce photographs containing any great amount of detail economically, yet it seems that the field remains sufficiently broad to warrant its development.

Inasmuch as the code system is not electric, except as concerns telegraph instruments, and does not introduce any new principle of physics or mechanics into the field of applied science it may, perhaps, not be of great interest, considered from a purely technical standpoint. Yet, inasmuch as it has been more or less successfully used in replacing more intricate systems the author thinks he is justified in discussing it in the present paper. A photogram, as it has been termed by the inventor, may be relayed any number of times, lends itself to wireless as well as wire telegraphy and is never subject to static and magnetic disturbances nor to the inherent evils of long telegraph and telephone lines; viz., capacitance, inductance, etc.

From the preceding description we may rightly conclude picture telegraphy is as yet far from the zenith of its possibilities. A broad field for investigation and experimentation in the application of new and untried laws and phenomena of chemistry, physics, etc.; as promulgated from time to time from the realm of pure science is unfolded to the engineer of tomorrow. Assuredly we may anticipate a great advance in this art during the next decade and we may be hopeful even of a practical solution to the problem of seeing over a wire or by wireless, in fact, some of the foremost European scientists are even now devoting their energies to this end.

Fig. 10a— Before Telegraphing: This is from the Original Photograph as it was taken at Sing Sing Prison, N. Y., Just After the Fire

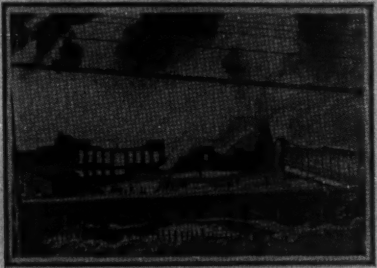
Fig. 10b—After Telegraphing: Picture of the Sing Sing Fire, Published by many Western and Pacific Coast Papers within Twenty-four Hours of the Fire—Really before the Fire was Out

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Discussion

R. J. C. Wood: Isn't the picture as received shown at Fig. 8 (D). I think that is actually what the receiving end gets over the wire and any exercise of imagination, as Mr. Hillebrand says, refers to (F). It would seem to me that these boundaries are determined by the co-ordinates of points along them, all around the boundary. That being so you then get these contour lines as shown on Fig. 8 (E). They are filled in with the particular shade according to one of the letters in the code corresponding to that boundary. You then get the Fig. 8 (E) as the final result received at the receiving end. The illustrator knows that nobody looks exactly like (D) and he makes it look a little better, like (8-F). Tele-photography means to a photographer taking very far distance scenes with a lens of long focus. Is this term telephotography standard in this sense of transmitting photographs to a distance by wire? The term is already fairly well assigned to the photographic science, and it would seem to me that some such title as photo-transmission or an equivalent would describe the process better than telephotography.

D. I. Cone: In that connection I note that the artist states "Under the second head which may be generally termed telephotography"—from which I gather that he is not satisfied that his word covers the subject. There are in the paper a number of references to the difficulties that have been encountered by workers on account of the inherent characteristics of the wire line. It seems to me that this is a hang over from earlier days when the transmission of signals over long electrical lines was less understood than it is now. As an example he states, "Interruptions to the circuit take place at an average speed of 250 times per second, a fact that renders its use on ordinary telegraph lines impossible since the relays in general use are of a low-speed type." That, while entirely true, is becoming less and less a limit, in fact it simply suggests that since he wants to use frequencies of the order of two or three hundred cycles per second he needs the telephone line as opposed to the ordinary telegraph circuit, or, what is equivalent to the same thing, the more recently developed carrier telegraph circuit which by merely modifying the terminal apparatus to handle higher frequencies is capable of caring for the high frequency on which his voids hinge. The earlier methods described in the paper can be said to have other difficulties at the present time entirely in the transmitting and receiving apparatus, and the question of troubles due to inductance and capacity on the line may be dismissed; and they say it is a bugaboo which can be most thoroughly taken into account to any degree of refinement that is necessary merely by spending a certain amount of money on it.

D. W. Isakson: As regards a name for the science of transmitting photographs over electric circuits I can only say that in this paper I have reverted to the term generally used and accepted by the technical and semitechnical press. An analysis of the word justifies its application. But as Mr. Wood points out it at present designates a division of photographic art and its inappropriateness therefore is not to be argued. It is to be expected that with the future development of the art appropriate nomenclature will be invented.

In the synopsis of this paper I have made the assertion that the solution to this problem of telegraphing pictures is near at hand. I have given no space to suggestions as to how this is to be accomplished. That the vacuum tube and carrier wave will play important roles in the development of picture telegraphy I have not the least doubt. In fact I am convinced that only by application of the carrier wave can it be made practicable, excepting perhaps radio. In this I have myself made some interesting experiments and hope to announce results in near future. Now as to Mr. Cone's suggestion of using telephone lines as a means of avoiding the difficulties encountered with low-speed relays, let me remind him of the telephone companies strict rules regarding the connection of foreign apparatus to its circuits. Neither is the low speed relay the insurmountable obstacle to success. It will be noted that in the Belin process and Liesdman's second system no interruptions take place. Here the current is continuous but varying in intensity. For this the vacuum tube relay has been used. The prohibitive cost of the arrangement with telephone and telegraph companies render both these systems impracticable from a purely economical standpoint. If by carrier wave we can send five or six photographs simultaneously and for the cost of, say two (allowing for added cost of apparatus) then we shall have taken a long stride toward ultimate success.

Recent Conclusions Pertaining to Electrical Precipitation

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Investigations into the phenomena of electrical precipitation of suspended particles from gases during recent years have resulted in some important conclusions. The purpose of this paper is to present these conclusions briefly, without entering into a detailed discussion of the actual equations used in designing precipitators, and of calculations embodying their use.

During the past few years considerable progress has been made in establishing an understanding of the relationship between the various factors entering into the phenomena of electrical precipitation of suspended particles from gases, and it is the purpose of this paper to set forth briefly some of the more important conclusions.

In the commercial application of the electrical precipitation process, as practised during the past ten years, many puzzling phenomena were encountered for which satisfactory explanations were entirely lacking. In fact, some of these phenomena appeared to be anomalies. As an example of such an apparent anomaly, we may take the relationship between precipitation efficiency and current flow. It had been early recognized that percentage of precipitation increased as the voltage approached the arcing point, and that the electrical discharge or current flow increased simultaneously and in a more or less definitely related manner. An apparent plausible conclusion was that precipitation efficiency was directly dependent upon current flow, and a review of the early work shows that much time and effort were expended in attempting to increase the corona discharge in certain commercial plants where precipitation results were lower than had been anticipated. Later, certain commercial problems were encountered where the very poorest results were obtained with the highest current flow, that is, with the most intense corona discharge. In fact, in one installation where the problem consisted of collecting thoroughly dry colemanite dust, at a California borax plant, the current could apparently be raised indefinitely without bringing about any appreciable precipitation results. The capacity of the electrical equipment at that plant was limited to 10 kw., but this total energy could be dissipated with ease in a 40-pipe precipitator without effecting any useful results.

For the purpose of this paper it will be unnecessary to enter into a discussion of the theory and practise of electrical precipitation, as these subjects have been thoroughly covered in published articles. For those who are not familiar with the subject, a selected bibliography is appended. Furthermore, R. B. Rathbun and G. H. Horne are presenting papers at this same meeting of the A. I. E. E., which review the subject briefly. For the purpose of this discussion, it is sufficient to say that electrical precipitation is accomplished by passing the fume-laden gas through a unidirectional electrostatic field in which a corona discharge is maintained. In practise, a precipitator consists of a multiplicity of opposing electrode units, one group being of such configuration as to facilitate corona discharge, the other group being of such form as to minimize or prevent discharge therefrom. The former are usually referred to as discharge electrodes, the latter as collecting electrodes. Discharge electrodes may consist of wires, chains, edged strips, serrated edges, or any other form of conductor that will establish a sufficiently high potential gradient at or near its surface to cause corona discharge. Collecting electrodes may consist of plates, pipes, screens, closely grouped wires, or any other form or arrangement of conductors that will establish low field concentration and thus minimize or prevent corona discharge therefrom. Usually the collecting electrode system is of much greater weight than the discharge electrode system, and consequently is electrically grounded. The discharge electrode

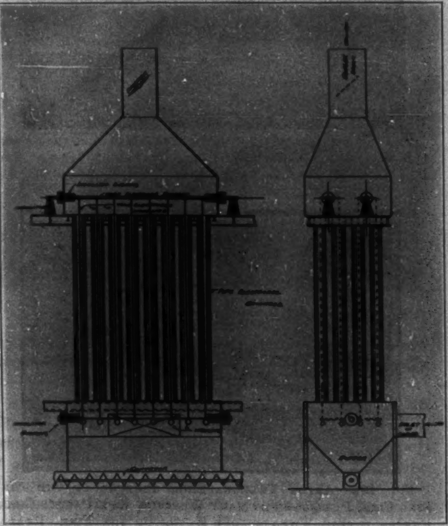

Fig. 1—Schematic Drawing of a Pipe Treater

Presented at the Pacific Coast Convention of the A. I. E. E., Vancouver, B. C., August 8-11, 1922.

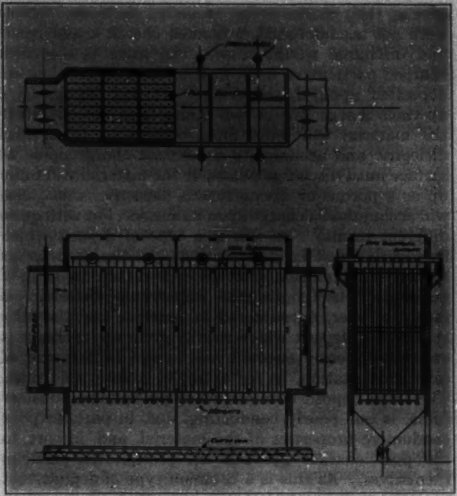

FIG. 2—SCHEMATIC DRAWING OF A PLATE TREATER

system is mounted upon insulators and is usually charged negatively with respect to ground. The potential difference maintained between electrodes depends upon the electrode spacing and other circumstances, and ranges in different installations from 20,000 volts to 100,000 volts. Unidirectional current is supplied by rectifying high-tension alternating current. The precipitator has been given the name of treater, and the type of collecting electrodes designates the type of treater, as, for example, pipe treater, plate treater, screen treater, etc. The principle of precipitation is in each case the same, the choice of treater depending on circumstances dictated by engineering considerations. Fig. 1 is a schematic drawing of a pipe treater; Fig. 2 is a similar schematic drawing of a plate treater; Fig. 3 is an illustration of a pipe treater installation; Fig. 4 gives a view of a plate treater; Fig. 5 shows a typical electrical control room, and Fig. 6 a typical wiring diagram.

FIG. 3—PIPE TREATER INSTALLATION

FIG. 4—VIEW INTO A PLATE TREATER

FIG. 5—TYPICAL ELECTRICAL CONTROL ROOM

EFFECT OF DEPOSITS

As already stated, it is sufficient for the purpose of this discussion, to consider that the fume-laden gas is passed through a unidirectional electrostatic field in which a corona discharge is maintained. However, it must be emphasized that this unidirectional discharge should emanate only from the discharge electrode and travel to the collecting electrode. We shall see that when this condition, which we can call normal, is disturbed, control of precipitation is lost and severe practical difficulties result.

For simplicity we can limit our immediate discussion to a small section of a pipe treater, that is, a short length of pipe, electrically grounded with a negatively charged wire placed along the axis of the pipe. When the voltage is raised above the critical potential, a corona discharge is established, the gas immediately around the wire becomes ionized, and the resultant ions travel either to the collecting electrode or to the discharge electrode, depending on whether they are negative or positive. However, those negative ions which once leave the zone of ionization, travel toward the collecting electrode and give up their charge to this grounded electrode. Should the gas in the tube carry suspended liquid or solid particles, such particles as come within the zone of ionization may become either negatively or positively charged and thus be either repelled from or drawn to the discharge electrode, while those particles which remain outside of the zone of ionization, become negatively charged and are forced over to the collecting electrode. In practise it is found that a certain amount of the precipitated material is always collected upon the discharge electrode, but by far the greater part of the precipitate is always collected on the grounded collecting electrode.

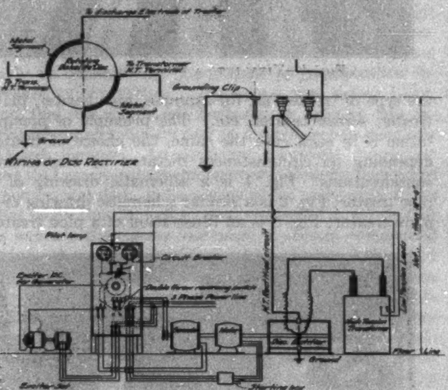

Fig. 6—Typical Wiring Diagram

However, as soon as material commences to collect upon the electrodes, conditions in the precipitator change. To refer again to our short tube: It was stated that the ions traveling to the collecting electrode must give up their charge to this grounded electrode. If this were not accomplished, a banked charge would result and discharge would cease. The same is true with charged particles of mist, dust or fume, when they are deposited upon the electrodes. If they do not give up their charge, one of two things must result; either the material will build up a continuous impervious dielectric and accumulate an electric charge upon its surface until discharge ceases, or the material will build up as a porous or discontinuous dielectric, which also will accumulate a charge upon its surface, but with quite different results. As this is a type of deposit which frequently must be dealt with in practise, it deserves special consideration and we will return to it in a moment. The continuous impervious dielectric is rarely, if ever, encountered in practise, and the fully conducting deposit which readily gives up its charge is only infrequently encountered, except in the case of mist precipitation, as for example, sulfuric acid mist. The usual deposit obtained when precipitating dust or fume, is but poorly conducting, due, in part, to poor conductive properties of the material, and, in part, to the poor contact between the precipitated particles themselves. As this is a common type of deposit, and as the handling thereof has presented many serious difficulties, we will be justified in discussing at some length its properties as well as its effects.

E. R. Wolcott has shown (*Physical Review*, N. S., Vol. XII, No. 4, October, 1918) that when a discontinuous dielectric covers an electrode, it acts in all respects as though the electrode had sharp projections at the points of discontinuity of the dielectric; that is, it establishes a point discharge. In other words, it establishes a discharge at the point of discontinuity, of a nature similar to the discharge that would result if the dielectric were replaced by projecting conducting points. It follows that such discontinuous dielectric, when placed upon an electrode, causes a lowering of the arcing voltage. A porous non-conducting deposit acts very similarly and apparently for the following reasons. Such a deposit consists of minute particles separated by equally minute gas spaces. As the solid particles and the gas will have different dielectric properties the electric field will be concentrated at the points of contact or approximate contact of the solid particles. As the charge accumulated at the surface of the deposit increases, and the field through the deposit increases, the field intensity at these points of local field concentration will rise sufficiently to cause ionization of the gas within the interstices in the deposit. Once this condition is established, the deposit becomes an ionizer or source of discharge, with most disastrous results so far as precipitation is concerned. In the first place, the gas immediately adjacent to the deposit becomes ionized and this results in a decrease in the dielectric strength of the gas between the electrodes and causes a lowering of the arcing voltage, as Wolcott has shown. Secondly, the deposit being an ionizer, causes an increase in discharge with consequent increase in power consumption. Thirdly, and most important, both electrodes become sources of discharge, and although instruments placed in the electric circuit will indicate a unidirectional current flow, still we will have two opposing discharges of opposite sign, one emanating from each of the two opposing electrodes. Any dust or fume particle placed between these two discharges will be buffeted back and forth, but may fail to be precipitated on the electrodes. In other words, such a deposit will cause three undesirable results, namely, lowering of the arcing voltage, useless dissipation of energy, and interference with normal precipitation. The following results obtained at a lead smelter, illustrate the effects resulting from the formation of such a deposit:

Condition of Deposit	Power Consumption	Precipitation Voltage	Precipitation Efficiency
Non-conducting........	7.2 K. W.	52,000 volts	74 per cent
Conducting............	5.0 K. W.	70,000 volts	97 per cent

As was stated early in this discussion, it is essential that the electric discharge shall emanate from the discharge electrode and travel to the collecting electrode if normal precipitation is to be accomplished. When materials are collected which tend to form porous dielectric deposits, it is, therefore, essential that conditions must be so changed as to prevent the formation of such a deposit. This can be done in several ways. The material to be precipitated may be changed through the introduction of substances which will cause the deposit to become conducting, as, for example, the addition of acid mist, carbon smoke, or any other convenient conducting material. Or, the gases may be so changed as to cause a surface leakage over the particles composing the deposit, which is often readily accomplished through the addition of moisture to the gases to increase the humidity thereof. Or, conducting materials may be added directly to the electrodes, as, for example, water or acid. Only a slight conductivity is necessary, as a current density as low as one milliampere per 30 sq. ft. of deposit is not uncommon. We are all familiar with the effect of humidity on the operativeness of electrostatic influence machines, where a slight surface leakage is sufficient to prevent the building up of a charge. A similar leakage is amply sufficient for drawing the charge through the deposit in a precipitator.

It is obvious that some deposits will exhibit much more serious effects than others, depending upon the degree to which they will accumulate a surface charge. In certain cases the discharge from the deposit, or back ionization, as it has been called, is sufficiently heavy to be clearly visible when viewed in the dark. Under such conditions, precipitation virtually ceases, the current flow will mount to many times its normal value, and the arcing voltage may be lowered as much as 50 per cent below its normal value. In other cases the back ionization is very mild and this will be manifested by a correspondingly small decrease in the arcing voltage. In such cases it often will be noticed, with a mixed dust and fume, that the decrease in efficiency will be greater on the fume than on the dust, possibly due to the fact that the relatively heavy dust particles can be shot through the thin reverse discharge caused by the back ionization, while the relatively light and small fume particles are arrested in their course, discharged, then recharged and repelled from the collecting electrode.

From a practical point of view, this can all be summarized by saying that the deposit upon the collecting electrode should, at all times, be kept conducting.

FACTORS BEARING UPON PRECIPITATION EFFICIENCY

A series of investigations recently conducted by E. Anderson and G. H. Horne, has disclosed some interesting and valuable information on the relationship between various factors bearing upon precipitation efficiency. This information can be summarized in a number of conclusions. Of primary importance is the relationship between precipitation efficiency and gas volume. Anderson has shown that the curve expressing this relation follows an exponential equation. Secondly, he has shown that with a given definite gas volume, the precipitation efficiency is a function of the length of discharge electrode and again follows an exponential equation. Thirdly, Anderson and Horne have shown that each combination of gas and fume has certain specific properties when considered from a precipitation viewpoint, and that these properties can be expressed numerically as a constant to be included in the precipitation equation.

The value of these three conclusions cannot be overestimated, as they bring order out of chaos in the mass of puzzling and apparently conflicting data that have been accumulated during the past ten years. All that is necessary now is to determine the value of the precipitation constant that applies to any specific problem, and all other considerations then follow in a perfectly orderly manner, according to definite mathematical relationships. The precipitation constant can be easily determined by experiment, or, where a familiar problem is under consideration, it may be drawn from experience. We will pass over the relationship between different types of electrodes, as discussion of these factors lies outside the scope of this paper, being in the province of the specialized engineer. The choice of type of treater, type and size of electrodes, electrode spacing, operating voltage, etc., are dependent upon engineering considerations, and can be dictated by experience only. The important generalized conclusion which it is desired to emphasize here, is that all types of precipitators behave in a similar manner, the effectiveness of one being expressible in terms of the other, and that after allowance is made for the type of treater, precipitation efficiency is then expressible in the terms of an exponential equation, which equation involves a precipitation constant expressing the properties of the fume-laden gas under treatment, and which has as its variables the length of discharge electrode and the gas velocity.

The following table shows the close agreement between calculated and observed values for precipitation efficiency:

Type of Treater	Character of Fume	Gas volume cu. ft. per min.	Efficiency	
			Observed per cent	Calculated per cent
Pipe..............	Potash fume	23,000	86	86
Plate..............	Potash fume	18,000	75	71
Pipe..............	Cement dust	150,000	94	92
Pipe..............	Metallic chloride	15,000	97	98.8
Pipe..............	Lead fume	102,000	82	85
Plate..............	Bismuth fume	5,000	90	92
Transverse screen	Potash fume	1,000	73	75

Considering the wide variation in both the character of fume and the gas volumes handled, the agreement between calculated and observed efficiency values is quite satisfactory.

With this definite knowledge at our disposal, it is now possible to calculate the optimum size of a precipitator for any specific commercial installation where the most economical recovery of valuable dust or fume is under consideration. A. A. Schmidt has developed a formula to be used for this purpose, which equation is of the form

$$x = a\left(\frac{\log \dfrac{b}{c \log d}}{\log d}\right)$$

In this equation a is the gas volume to be treated, b is a function of the unit cost of the precipitator, the rate of interest and depreciation and cost of labor and power. The value of the solids carried by the gases is represented by c, d is a function of the specific precipitation rate for the fume or dust considered, and x is the optimum size of the precipitator.

It should be emphasized that the equations pertaining to precipitation efficiency apply only while normal precipitation is being performed. If a porous dielectric deposit is accumulated upon the electrodes and back ionization is established, normal precipitation is obviously interfered with and these equations can no longer be applied.

It should also be emphasized that the precipitation constant is in itself a variable and that its value is only constant for a specific set of fume and gas conditions, and shifts with changes in gas composition, temperature, fume composition, fume concentration, physical state of subdivision of dust or fume, etc.

To make these last statements clear, it might advantageously be said that it is not only the average value of the precipitation constant that is of interest in designing a commercial installation, but consideration must also be given to the limits through which the value of this constant will fluctuate with variations in factory operations. For example, in treating the gases from a single copper converter, different precipitation constants apply at different stages in the converting operations. If the matte fed to the converter contains appreciable quantities of lead and zinc, the gases arising from the first part of the blast will carry a lead and zinc fume, while during the latter part of the blast the gases will carry essentially fine copper pellets or dust mixed with some copper fume. Also, a constantly rising temperature must be dealt with. Furthermore, as lead and zinc fumes have the faculty of forming deposits which easily lead to back ionization, care must be taken to insure at all times the deposition of a conducting deposit. In designing a plant to take care of such a problem, a precipitation constant must be chosen which will represent the most difficult conditions to be encountered under the varying operating conditions. The example chosen is, of course, an extreme case, and the engineer is rarely called upon to design a plant to operate on such a varying load. Usually the precipitation constant will vary within rather close limits, and ordinarily these limits can be readily determined before design of precipitator is undertaken.

Anderson and Horne, in their investigation, have again confirmed earlier determinations upon the effect of voltage. It is now clearly established that precipitation efficiency rises rapidly as the voltage increases, and that for best results, the voltage on a precipitator should be kept as near the arcing point as is consistent with smooth operation. As voltage has a direct bearing upon precipitation efficiency, the question will be asked as to why this variable has been ignored in the previous discussion. This is because commercial installations are always operated at the maximum stress permissible with smooth operation, and consequently the voltage variable can be disregarded.

The purpose of this paper is merely to present some of the conclusions which have been drawn from recent investigations, and to make these available to the engineer. A detailed discussion of the actual equations used in designing precipitators, and calculations embodying their use, have been purposely omitted because, after all, the choice of precipitator types and the analysis of the factors entering into the phenomenon of precipitation, can be properly accomplished only by the experienced specialized engineer, and his ability to do this is part of his stock in trade. However it is hoped that present-day conclusions have been sufficiently clearly and fully set forth to show that the former puzzling and perplexing data and apparent anomalies have been coordinated into a consistent whole, and that, after all, the phenomenon of precipitation is consistent as well as relatively simple in its essential fundamentals.

SUMMARY

1. Many types of fume and dust when deposited on the electrodes comprising an electrical precipitator form porous dielectric deposits.

2. Such deposits establish back-ionization and will cause three undesirable results, namely, lowering of the arcing voltage, useless dissipation of energy, and interference with normal precipitation.

3. To prevent the formation of such deposits, conditions must be so changed as to insure the deposition of an electrically conducting deposit. This can be accomplished in several ways.

4. The relationship between precipitation efficiency and gas volume can be expressed by an exponential equation.

5. For a definite gas volume, precipitation efficiency is a function of the length of discharge electrode and also follows an exponential equation.

6. Each combination of gas and fume has certain specific properties when considered from a precipitation viewpoint, and these properties can be expressed numerically as a constant to be included in the precipitation equation.

7. All types of precipitators behave in a similar manner, the effectiveness of one being expressible in terms of the other.

8. After allowance is made for the type of treater, precipitation efficiency is then expressible in terms of an exponential equation, which equation involves a precipitation constant expressing the properties of the fume-laden gas under treatment, and which has as its variables the length of discharge electrode and the gas velocity.

9. With this definite information available, the optimum size of precipitators can be calculated.

10. The equations pertaining to precipitation efficiency only apply while normal precipitation is being performed and do not apply when the deposit on the electrodes establishes back-ionization.

11. Precipitation efficiency rises rapidly as the voltage increases and commercial installations should be operated at the maximum stress permissible with smooth operation.

12. The precipitation equations and calculations embodying their use are omitted for reasons set forth.

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Discussion

For discussion of this paper see page 826.

Electrical Engineering Features of the Electrical Precipitation Process

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Review of the Subject.—*In the beginning, the Cottrell Process of Electrical Precipitation was greatly handicapped by the fact that there did not exist standard electrical equipment which could be used to develop the necessary potentials under the severe conditions imposed by the mechanical rectifier, used for rectifying the high-potential alternating current. The transformers used were a constant source of trouble and annoyance. This condition delayed the rapid accumulation of accurate data pertaining to precipitation phenomena, since those engaged in the work were kept busy in merely maintaining a source of power.*

It was not long, however, before the electrical manufacturing companies were interested in the problems involved, and better transformers were produced. These transformers have now been developed to a degree which is very nearly the equal of the ordinary power transformers of the same voltage ratings. For several years there was a demand for higher and higher voltage ratings, owing to the belief that through the use of very high potentials and consequent large electrode spacing the size and cost of precipitators could be greatly reduced. Potentials as high as 250,000 volts were experimented with, but such high voltages proved to be impractical.

Transformers as now standardized are in two voltage ranges, one with a maximum voltage of 75,000 volts having taps in the low tension to deliver 50, 60, 65 and 70 kilovolts, the other having a maximum voltage rating of 100,000 volts with taps in the low tension to deliver 50, 62½, 75 and 87½ kilovolts. These transformers are manufactured in 10, 15 and 25 kv-a. capacity.

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Review of the Subject. (250 w.)
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Power Consumption. (1800 w.)
Conclusion. (135 w.)

SOURCE OF POWER

In all plants in commercial operation today the low-tension current is supplied to the transformer in accordance with one of two systems. These are known as the synchronous motor system and the motor-generator system, and are shown by the wiring diagrams, Figs. 1 and 2 respectively.

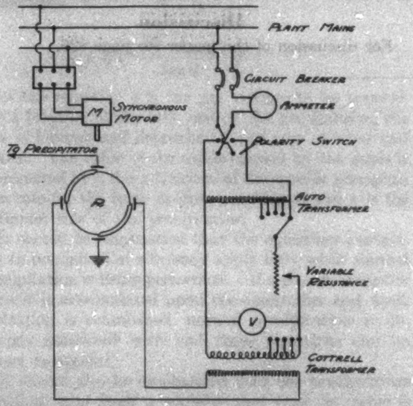

Fig. 1—Wiring Diagram—Synchronous Motor System

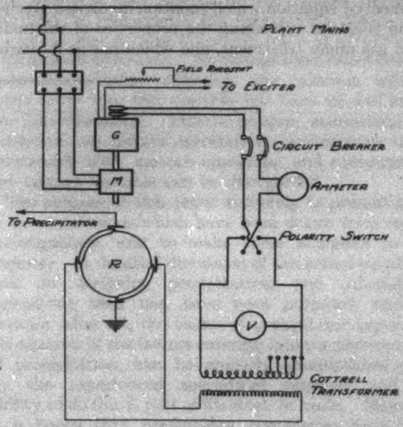

Fig. 2—Wiring Diagram—Motor-Generator System

In the synchronous motor system, the power is supplied to the transformer from one phase of the regular factory three-phase main. The mechanical rectifier is driven by a synchronous motor from which this system derives its name. This motor is usually a three-phase synchronous motor and is self-starting. It consists of a standard four-pole induction motor in a 3 horse power frame, the rotor of which has been slotted or under cut at four places in its circumference to emphasize the poles. As built, the best types of these motors possess the ability to pull into synchronism on voltages as much as 30 per cent below normal, and will deliver approximately two h. p. without slip. The greatest advantage of this system is its low cost. Where this system is employed, care must be taken in starting up to apply negative polarity to the electrode system. This is indicated by a spark gap at the rectifier and

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Presented at the Pacific Coast Convention of the A. I. E. E., Vancouver, B. C., August 8-11, 1922.

controlled by a polarity switch. The voltage regulation is usually accomplished by a variable resistance in connection with taps in the low tension of the transformer winding, although in some cases auto transformers or induction regulators or any combination of these are in use. As stated above, in this system the transformer is connected directly to the plant mains and this has been the source of much discussion in connection with disturbances in the precipitation circuits being reflected back on these mains, but tests which are borne out by experience show that any such disturbances do not manifest themselves in external circuits.

In the motor-generator system a motor is used to drive a single-phase four-pole generator which supplies power through the switchboard to the low-tension windings of the transformer, and this motor is also coupled to the rectifier. As the generator and rectifier are mechanically connected, the latter is always in synchronism with the current which it is rectifying. In this system the voltage regulation is secured by means of the generator field rheostat in connection with the taps in the low-tension winding of the transformer. There is no electrical connection between the precipitation circuits and the factory mains, and this eliminates all possibility of disturbances passing from one to the other.

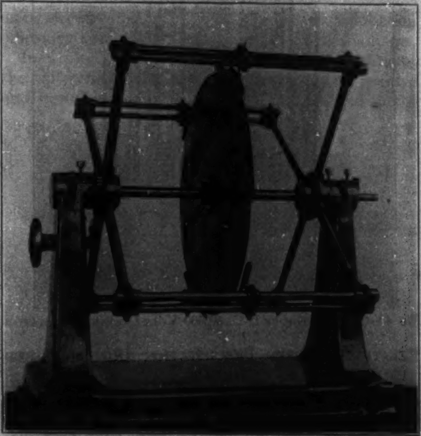

FIG. 3—MECHANICAL RECTIFIER

A third system has been proposed which, however, has never been used. In this the transformer would be eliminated and power taken directly from existing high-tension power lines through proper protection and switching devices, and the current rectified by a synchronous motor-driven rectifier. This system will probably never come into actual use as it is doubtful if any company would care to connect a high-tension line to this class of service.

There is no marked difference in the precipitation results obtained from either of the two systems in use, as the same voltage can be maintained on the precipitator by either system, and insofar as power supply is concerned, precipitator voltage is the important factor bearing upon precipitation efficiency.

METHODS OF RECTIFICATION

As indicated above, it is necessary to supply the discharge electrode system with unidirectional current in order to obtain maximum precipitation efficiency. This does not mean that a regular direct current is necessary. In fact, it has so far not been definitely proved that direct current possesses any inherent advantage over the pulsating unidirectional current obtained through the use of the mechanical rectifier.

A typical mechanical rectifier is illustrated in Fig. 3. It consists of a bakelite disk to the periphery of which are attached two quadrant metal strips opposite each other, these constituting the moving conductors. The four stationary shoes are so mounted that they may be rotated about the disk through 90 deg. by means of a hand wheel, pinion and gear segment. The length of the stationary shoes and the length of the moving conductors determine the length of contact on the wave, and the position of the shoes about the disk, as adjusted by the hand wheel, determines the portion of the wave rectified. On the rectifier illustrated, the shoes cover approximately 25 per cent of the wave. Mechanical rectifiers of this general type are the only rectifiers which have so far proved successful in commercial operation, and, as a result, are the only kind in use at this time. While they are far from perfect in many respects, they do possess the advantage of substantial construction and simplicity of operation requiring a minimum of attention. In other words, they embody features of reliability not yet attained in other types. The greatest single objection to them is that the high-tension circuit is made and broken in air, generating high-frequency oscillations, which place abnormal electrical strains on the transformer. Apparently these oscillations do not markedly affect the efficiency of precipitation, at least no tests have shown any appreciable lowering of efficiency from this cause. Another objection to the mechanical rectifier is that it is noisy in operation due to the arc which is drawn out at the trailing end of the rotating segments. However, the noise as well as the oscillations may be fairly well damped out by the use of proper resistance in the high-tension circuits. A further objection to the mechanical rectifier is its low efficiency due to the air gap which must be broken down at each of the stationary shoes. There is an unavoidable voltage drop over the rectifier and it has not been found possible to eliminate this, owing to the high peripheral speed of the disk, which makes metallic contacting impractical.

Another type of rectifier is the kenotron, which is a vacuum tube conducting current in one direction only by means of electronic emission from an incandescent electrode. This type of rectifier has many promising features as it does not possess a number of the disadvantages of the mechanical rectifier. However, such rectifiers have the disadvantage of being fragile and consequently require much care in handling. Moreover they do not stand short circuits and must be protected by a system of automatic relays since short circuits in the precipitator may be of frequent occurrence. The current-carrying capacity of such a rectifier is limited by the rate at which electrons are liberated from the incandescent filament. The life of such a rectifier is limited, but with the kenotron this has now been extended to approximately 2500 hours. As yet, no large commercial precipitation installations have been made with kenotrons as the sole means of rectification. Investigations are now under way at one of the larger smelters in the United States in which comparative studies are being made of the kenotron and the mechanical rectifier with the object of determining their respective merits over long periods of operation.

A third method of rectification is by means of the air blast rectifier. This method has not been carried beyond the experimental stage as it was found to possess all of the disadvantages of the mechanical rectifier in an aggravated form. This rectifier consists of a discharge point facing a plate. The pointed rod is located so as to project from a tube through which compressed air is blown around the point toward the plate. This apparatus acts as an electric valve, allowing only the positive discharge to flow across the gap to the plate. The only advantage which rhe air blast rectifier possesses is cheapness.

DIRECT CURRENT

So far as is known, there has been only one serious attempt made to produce a direct-current generator for precipitation work. This was made several years ago by the Girvin Electrical Development Company of Philadelphia, working in conjunction with the Research Corporation of New York. Several machines were built of about 10-kw. capacity which delivered current at 50,000 volts. Also one 75,000-volt generator was built. Fig. 4 shows the commutator of one of these generators. These machines were of the vertical type, belt-driven, with a rotating field and provided with intermediate commutating poles. The armature coils were submerged in oil. The case carrying this oil being partly located in the magnetic field, was made of bakelite. The individual coils of the armature were brought up to a commutator which consisted of a number of disks one of which served as a commutator for each armature coil. The disks were interconnected so as to add the voltages of all coils and deliver the power to a single high-tension lead. The other end of the system was grounded. These machines were 33 inches in diameter and 62 inches high, making a very compact unit when the capacity and voltage rating are considered.

Comparative tests made between one of these generators and a mechanical rectifier indicated that the generator gave slightly better results, so far as precipitation efficiency is concerned, but the superiority was not sufficiently great to warrant further development work.

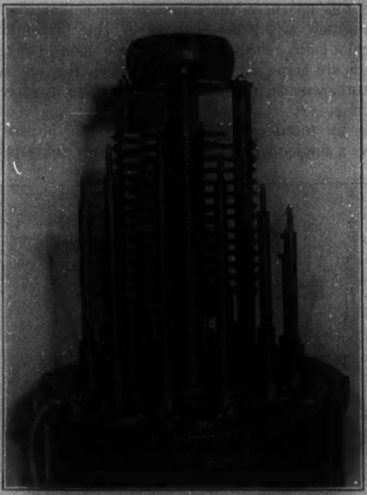

FIG. 4—COMMUTATOR OF D-C. 50,000-VOLT GIRVIN GENERATOR

RELATION BETWEEN PRECIPITATION AND IMPRESSED VOLTAGE

In the foregoing discussion the main features of the apparatus and methods used in producing a source of power for electrical precipitation work have been discussed. It is interesting to note some of the relations between voltage and precipitation efficiency.

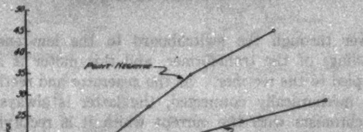

FIG. 5—ARCING VOLTAGE BETWEEN POINT AND SPHERE AT SHORT DISTANCES

The measurement of voltage by means of the needle point spark gap, is well-known. If one of the needles is replaced by a smooth, clean flat plate, we have what is analogous to a precipitator, the needle point corresponding to the discharge electrode and the plate to the collecting electrode. With such a "point to plate" arrangement, laboratory studies may be made of some of the fundamental factors involved in electrical precipitation. It can be shown that rupture, or complete electrical breakdown, of the air between the point and plate for most spacing will take place at widely different voltages, depending on whether the point is positive or negative. This is shown by the two curves of Fig. 5. It will be noted that the curves cross at about 2 mm. and that at shorter distances the arcing voltage is greater when the point is positive, while for all spacings above 2 mm. the arcing voltage is greater when the point is negative. This is one reason why the use of negative polarity on the discharge electrodes in electrical precipitation is preferable. A second reason for using negative polarity is that usually the precipitation efficiency is higher even with equal impressed voltages.

In a precipitator, under actual working conditions, the difference in the arcing voltage between positive and negative polarity is not so great as found in the point to plate investigation in the laboratory, results of which are indicated in Fig. 5. However, there is usually a substantial difference in favor of negative polarity.

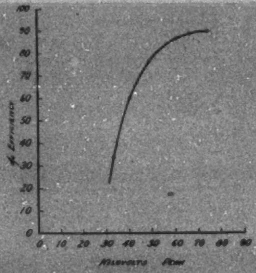

FIG. 6—RELATION BETWEEN PRECIPITATION EFFICIENCY AND PEAK KILOVOLTS IMPRESSED ON PRECIPITATOR
Typical Curve

Fig. 6 illustrates the relation existing between the voltage impressed on a precipitator and its precipitation efficiency when treating gas at a given rate. If this rate be changed, the curve would be shifted above or below the curve shown. It will be noted that this curve flattens out toward the top and the higher voltages are not accompanied by a corresponding increase in efficiency. The highest point shown on the curve in Fig. 6 is 2000 volts under the normal arcing voltage of the precipitator on which the tests were made. This curve, therefore, shows the fallacy of the belief which has often been expressed in the past, namely, that the last few volts, just under the arcing voltage, are particularly effective.

The fundamental differences between the positive and negative discharge as they affect precipitation, are not well understood. A visual difference is observed in the corona of the two. The positive corona manifests itself in rather long shifting brushes, while the negative is of a steady, bright beadlike character. From such an observation it may be concluded that with positive discharge the gas is ionized to a greater distance from the conductor than with the negative discharge. On the basis of this assumption, it is not surprising that the arcing distance for a given voltage is greater when the point is positive than when it is negative.

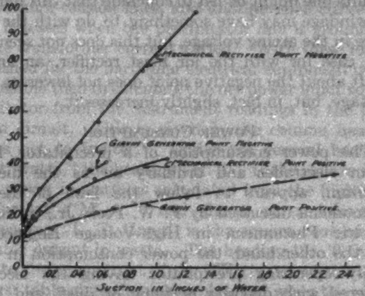

FIG. 7—RELATION OF SUCTION CAUSED BY ELECTRIC DISCHARGE, TO PEAK KILOVOLTS
Point mounted 6 cm. above grounded plate

In connection herewith, some study has been made of the electric windage established about a discharging point. This was done by using the point to plate method described above, with the exception that in this case the pointed rod was hollow, the discharge taking place from the rim of a hole 0.04 inch in diameter. This pointed rod was fitted to a brass tube and was connected to a draft gage by means of rubber tubing. Fig. 7 shows curves of the results obtained with a constant spacing of 6 cm. between the point and plate. The curves marked "Girvin" are those obtained with the 50,000-volt generator previously described. The other two curves were obtained by using a mechanical rectifier. It will be noted that in all cases, the suction created about the point is several times greater when

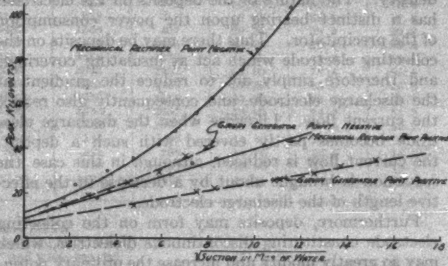

FIG. 8—RELATION OF $\sqrt{\text{SUCTION}}$ CAUSED BY ELECTRIC DISCHARGE, TO PEAK KILOVOLTS
Point mounted 6 cm. above grounded plate

the point is positive than when it is negative. From some further calculations and curves which are shown in Fig. 8, it seems that the suction established around the positive point follows a quadratic law so that the square root of the suction is proportional to the voltage. The suction created by the negative point, however, apparently does not follow the same law. From these results one might be led to conclude that this difference in windage may have something to do with the difference in the arcing voltage, but this does not seem to be the case for with the air blast rectifier, an artificial draft about the negative point does not lower its arcing voltage, but, in fact, slightly increases it.

POWER CONSUMPTION

The power consumption of a precipitator, having clean electrodes and ordinary air as the dielectric medium, appears to follow the laws of dielectric phenomena discussed by F. W. Peek, Jr., in his "Dielectric Phenomena in High-Voltage Engineering." On the other hand, the power consumption in a normally operating precipitator having the electrodes covered with deposits of fume or dust, and having furnace gases as the dielectric, is influenced by a number of factors which have not as yet been fully investigated.

Gases arising from combustion or other chemical reactions may be highly ionized, and the current flow will consequently be increased unless means are employed to remove the ions before the gases reach the precipitator. Then, too, the temperatures of the gases may be as high as 600 deg. cent., and this in itself may cause variations over and above those which would be expected from the corresponding reduction in the gas density. The nature of the deposits on the electrodes has a distinct bearing upon the power consumption of the precipitator. Thus there may be deposits on the collecting electrode which act as insulating coverings, and therefore simply act to reduce the gradient at the discharge electrode, and consequently also reduce the current flow. Likewise when the discharge electrode becomes partly covered with such a deposit, the current flow is reduced, although in this case the reduction is brought about by a decrease in the effective length of the discharge electrode.

Furthermore, deposits may form on the collecting electrode constituting discontinuous dielectrics, which may so greatly modify and increase the ordinary potential gradient near the surface of this electrode as to cause ionization to set in at this electrode also. An effect is thus produced which so far as power consumption is concerned, is equivalent to an increase in the length of the discharge electrode.

Although few data have been accumulated on the quantitative effect of such deposits on the power consumption, the effects of such deposits on the arcing voltage and on precipitation have been discussed in the literature[1] on the subject.

The following table will serve to show how much deposits may modify the ordinary operating conditions. This table was made up from data obtained by E. R. Wolcott and the writer, and shows the effect of such deposits on the arcing voltage between a point and a plate, six centimeters apart:

Material on plate		Arcing voltage kv. peak
Plate clean	point negative	120
Mica	" "	50
Sulphur	" "	50
Glass wool	" "	50
Varnished cambric	" "	70
Filter paper	" "	90
Writing paper	" "	118
Writing paper crumpled	" "	90
Edge of glass plate	" "	65
Asbestos	" "	100
Plate clean	" positive	45

From this table it is seen that the greatest effect produced by any of the materials is not as pronounced as that caused by reversing the polarity of the point. Apparently a minimum arcing voltage is reached with the point positive, and the effect of deposits on the plate under a negative point is to lower the arcing voltage to a value which approaches that when the point is positive. So far as is known, no material has been found which reduces the arcing voltage with the point negative to a value as low as that which applies when the point is positive. On the other hand, no materials have been found which lower the arcing voltage when the point is positive. In fact, it has been shown that a point may be substituted for the plate when the plate is negative without lowering the arcing voltage.

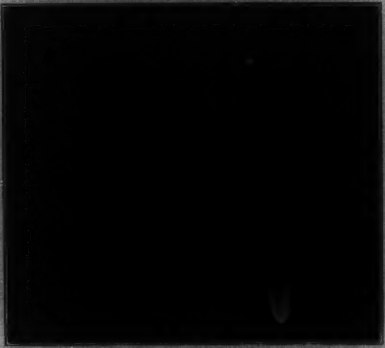

FIG. 9—CORONA FORMED AROUND HOLE IN MICA SHEET PLACED UPON POSITIVE PLATE

The effect of a discontinuous dielectric is illustrated in Fig. 9, which is from a photograph of the corona formed at the positive plate, by a thin sheet of mica having a small hole. Naturally, the current flow and power consumption must be tremendously affected by conditions such as these, and the problem of obtaining consistent data from different installations is very difficult.

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[1] E. R. Wolcott, *Physical Review*, N. S. Vol. XII, No. 4, October, 1918, and E. Anderson, *Chemical and Metallurgical Engineering*, Vol. XXVI, No. 4, January 25, 1922.

However, there are installations where the above mentioned disturbing influences are a minimum. Data from such installations indicate that Peek's fundamental equation for corona loss does apply, at least approximately. This equation is:

$$P = C^2 (e - e_0)^2$$

For the purposes of precipitation calculations, let

P = power required in watts

e = voltage impressed on treater in kilovolts peak

e_0 = the critical disruptive voltage in kilovolts peak

C = a factor representing the slope of a line resulting from plotting $\sqrt{P}$ against e

The following are representative tabulations of the power data obtained when 112 pipes 8 inches internal diameter by 13 feet 0 inches long were energized at various voltages. While the pipes used in these tests were of wood, they possessed good conducting qualities since the material collected was a mist of salt solution, and the pipes were, therefore, moist and impregnated with salt:

The columns headed "Losses" represent the losses between the input to the transformer and the input to the precipitator. These losses were established in the same manner that is used to determine iron and copper losses in transformers, *i. e.*, by establishing one curve of losses when the precipitator is disconnected with various voltages impressed on the transformer, rectifier and high-tension lines, and another such curve for the $I^2 R$ losses when the precipitator line is grounded, and the transformer current varied. With these losses established for the particular electrical equipment used, it is possible then to calculate the net power input to the precipitator from the instrument readings in the low-tension circuit. This is given in the column headed "Watts net to treater." Under the general heading "Sq. rt. watts," the heading "H. T." is the square root of the power in watts as calculated from the high-tension current ("M. A.") and the r. m. s. kilovolts. The heading "L. T. Gross" is the square root of the generator output in watts. The heading "L. T. Net" refers to the square root of the "Watts net to treater." The first table gives the values obtained when the pipes contained still air at 70 deg. fahr. The second table

TABLE 1—POWER DATA

112 Pipes 8 inches internal diam. by 13 ft. 0 in.
With Still Air at 70 deg. fahr.

(See Figs. 10 and 11.)

High Tension				Low Tension					Sq. Rt. Watts		
Peak Kv.	R. M. S. Kv.	M. A.	Watts	Volts	Amperes	Watts	Losses Watts	Watts Net to treater	H. T.	L. T. Gross	L. T. Net
13	10.8	2.2	24	80	0.0	200	275	0	4.9	14.1	0.0
14	12.8	5.6	72	100	0.0	334	320	14	8.48	18.2	3.7
17	14.3	8.0	114	110	0.0	434	348	96	10.68	20.8	9.8
19	15.3	14.0	214	120	2.0	667	428	239	14.62	25.8	15.4
20	15.8	17.5	276	130	8.0	900	630	270	16.60	30.0	16.4
22	16.8	21.0	353	140	13.0	1134	818	316	18.78	33.7	17.8
24	17.8	28.0	498	150	19.0	1467	1060	407	22.30	38.3	20.3
26	20.2	56.3	1137	160	27.5	2667	1442	1225	33.70	51.6	35.0
31	22.2	77.0	2150	170	46.0	4834	2455	2379	46.40	69.5	48.8
34	23.7	113.6	2669	180	54.0	6000	3043	2957	51.80	77.4	54.4
35	24.2	137.4	3320	190	62.5	7234	3765	3469	57.60	85.0	58.9
38	26.2	166.0	4350	197	74.0	8667	4852	3815	65.90	93.1	61.7
32	23.7	123.0	2870	180	51.5	5500	2863	2637	53.60	74.2	51.3
28	21.2	80.0	1695	160	36.0	3667	1842	1825	41.15	60.5	42.7
16	13.3	11.6	154	110	0.0	434	348	96	12.40	20.8	9.8
19	14.8	15.0	222	120	2.0	667	428	239	14.90	25.8	15.4
22	16.8	23.3	392	140	12.0	1000	783	217	19.80	31.6	14.7
26	22.2	76.7	1702	160	36.0	3734	1842	1892	41.25	61.1	43.4

TABLE 2—POWER DATA

112 Pipes 8 inches internal diam. by 13 ft. 0 in.
With gas at 170 deg. fahr. and 9 feet/sec. vel.

(See Figs. 10 and 11.)

High Tension				Low Tension					Sq. Rt. Watts		
Peak Kv.	R. M. S. Kv.	M. A.	Watts	Volts	Amperes	Watts	Losses Watts	Watts Net to treater	H. T.	L. T. Gross	L. T. Net
51	39.5	146	5770	216	64	9667	4082	5582	76.0	98.3	74.7
47	36.0	128	4610	205	58	8170	3480	4690	67.8	89.8	68.5
41	31.6	130	4110	200	57	7667	3370	4297	64.1	87.6	65.5
38	30.1	106	3210	190	48	6000	2685	3315	56.6	77.4	51.6
32	24.6	36	900	170	20	1900	1195	705	30.0	43.6	26.6
30	23.7	28	664	160	15	1367	972	395	25.7	36.9	19.9
28	23.0	21	483	150	10	1067	760	307	21.9	32.6	17.5
26	22.2	16	355	140	5	734	573	161	18.8	27.1	12.7
22	19.7	8	176	120	0	334	378	0	0.0	18.2	0.0
26	22.2	19	422	140	5	834	573	261	20.5	28.9	16.2
30	24.2	28	678	160	16	1434	997	437	26.0	37.8	20.9
36	27.1	92	2490	180	43	5134	2363	2771	49.9	71.6	52.6
39	29.1	124	3610	190	56	6867	3235	3632	60.0	82.8	60.2
41	30.6	152	4650	200	67	8667	4240	4427	68.2	93.1	66.5

gives the values obtained when the treater was operating on a mist-laden gas at the temperatures and velocity indicated.

Fig. 10 shows two lines plotted from the above data, one for air and one for mist-laden gas. In this case the square root of the generator output (input to transformer) in watts (column marked "L. T. Gross") is plotted against the voltage impressed on the precipitator in kilovolts peak. It is possible to use the generator output in this way as well as the net input to the treater, because the losses are principally made up of $I^2 R$ losses in the transformer and at the rectifier. At least the evidence of the curves indicates that there is little error introduced by so doing. The peak voltage has been used instead of the r. m. s. because of the comparative ease of obtaining readings in terms of peak voltage.

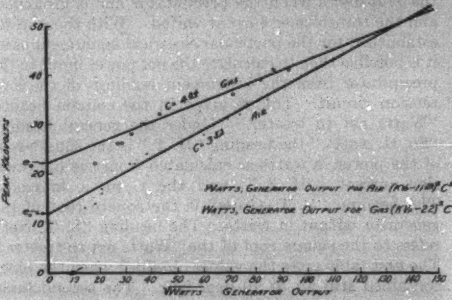

FIG. 10—POWER DATA PLOTTED—PIPE PRECIPITATOR

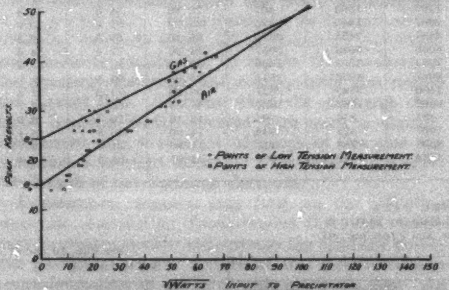

FIG. 11—POWER DATA PLOTTED—PIPE PRECIPITATOR

From an inspection of these curves, the differences in the values of e_0, and of C, the slope of the lines will be noted. It will also be seen that the power for the "air" curve is greater than for the "gas" curve, up to a voltage of approximately 50 kv., where the curves intersect.

Fig. 11 shows similar curves plotted against the square root of the net power input to the treater. The values of the power as obtained from the low-tension readings are seen to be in fair agreement with those obtained directly from the high-tension instruments. These curves also show the same relative values of e_0 and C as in Fig. 10.

It is, of course, impossible to draw any general conclusions from the data here presented, except that it appears the power consumption does follow the quadratic law given by Peek, and that this law is applicable to electrical precipitation. However, it should be said that certain experimental data indicate that the fume or dust carried in suspension in the gases may affect the electric discharge and may decrease the power consumption. From the increase in the value of e_0 for "gas" over that for "air," shown in the curves, it might further be concluded that fume also may cause a considerable increase in the corona starting voltage.

The foregoing data and discussion show that Peek's expression for corona loss may be used as a means of interpreting electrical precipitation power data.

SUMMARY

1. Power is supplied to precipitation plants by two systems, viz., the synchronous motor system and the motor-generator system.
2. The high-tension unidirectional current employed is obtained by rectifying the current from the high tension of a single-phase transformer.
3. Various types of rectifiers have been employed, including the kenotron, the air blast rectifier and the mechanical rectifier, the latter having so far given the most all around satisfaction.
4. Direct current at high potential has, so far, not shown any inherent advantage over the pulsating unidirectional current obtained from the mechanical rectifier.
5. The arcing voltage between a point and plate, which is analogous to a precipitator, is determined by the polarity of the point. At spacings in the neighborhood of 5 cm. between the point and plate, the arcing voltage for the point negative is roughly double the arcing voltage with the point positive.
6. At the same impressed voltage, the negative polarity is more effective in precipitation than the positive. Consequently the discharge system of a precipitator is maintained at a negative potential with respect to the collecting members.
7. The amount of windage or draft created about a discharging point in the "point to plate" arrangement is also determined by the polarity of the point.
8. Certain materials when placed on a plate under a negative point in the "point to plate" arrangement possess the ability to lower the arcing voltage to a value nearly equal to that caused by reversing the polarity of the point.
9. Peek's fundamental equation for corona loss apparently may be used to express the power consumption of precipitators.

Discussion

For discussion of this paper see page 826.

Electrical Precipitation of Solids From Smelter Gases

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Review of the Subject.—*The fundamental principles of the process in its simplest form are set forth. It is shown why the Cottrell process during recent years has in a large measure supplanted the bag-house and dust chamber in treating smelter gases.*

The commonly accepted theory concerning the manner in which the dust particles is charged and precipitated is given. It is pointed out that the thing most important to the operating man is how the particles may be enabled to give up their charge to the electrodes under all conditions, rather than the manner in which they receive it.

The various types of treaters in common use are described and discussed. The advantages of straight line treaters over those in which the gases are by-passed are emphasized.

It is shown that the gas is ionized much more efficiently for a given power consumption and the construction simplified and reduced by arranging the electrodes in the flue so that their electric fields are in series with each other. It is shown that this is accomplished by causing the gas to flow parallel to the electrostatic lines instead of at right angles to them, as in all other types.

The factors of lead and copper metallurgy are given which control the amount of sulphuric acid and water vapor in the gases. It is also pointed out that these things are a measure of the successful operation when treating smelter gases.

The physical rather than the chemical structure of the dust in suspension is shown to be the all-important matter. Several theories are given as to why flue dust is so much easier precipitated than fume. A number of photo-micrographs are given to illustrate the difference in physical structure between fume and dust.

Two methods are featured of obtaining sufficient conductivity in a dry precipitated coating to permit the electric charge to leak through it to the electrode. The theory of selective absorption is advanced as an explanation of how aqueous vapor added to the gas stream functions in this respect. The method of adding very finely atomized sulphuric acid is shown to be the most practical, it not having certain disadvantages of the water and its higher boiling point permitting a wider field of application. Its action is shown to be due to the fine acid particles being precipitated with the dust particles thereby imparting conductive film to the particles by diffusion.

The amount of free sulphuric acid in grams per 1000 cu. ft. of gas which permits a good precipitation on gas without conditioning is given from tests made on a large installation.

The theory of back ionization and phenomena of discontinuous dielectric are discussed.

Electrical matters are shown to be secondary to treater design and to the conditioning gas. All that can be expected of electrical equipment is to stress the space between electrodes to the economical limit. Local conditions must govern choice of electrical equipment.

The tendency to regard electrical phenomena, such as surging which as a rule accompanies poor precipitation as causes rather than effects, is cited. Effects of conditioning gas in reducing surges is shown.

Internal reactance in transformer best suited to precipitation work is discussed, also possibility of exceeding the practical limit and wasting power on treatable gas by carrying voltage up to the point of disruption; necessity of knowing electrical values in the treater, and these are best obtained with milliammeter and electrostatic voltmeter; finally, the subject of proportioning the plant investment between electrical equipment and treater is covered.

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INTRODUCTION

In presenting this paper on the application of this process to smelter gases it is with the view of lending practical assistance to the engineer engaged in the smelting industry and furnishing useful information to others interested in the process.

The subject will be covered from the viewpoint of the engineer whose watchword must always be "return on the investment" rather than that of the physicist. However, consideration will be given to such theoretical matters as seem to have a practical bearing.

For the information of those not familiar with the metallurgy of copper and lead a short review will be made of that portion of the subject affecting the adaptation of the Cottrel process.

The present scope and diversified applications of the process preclude a complete discussion in this paper, but the general principles are sufficiently covered to insure an understanding of their application to smelter gases. The essentials are stressed and the non-essentials pointed out. Among the things featured are economy of treater design and methods of treating gases carrying solids difficult to precipitate, the solution of which will materially extend the scope of the process in the metallurgical field.

DESCRIPTION

The process which the genius and foresightedness of Dr. F. G. Cottrell gave to the world in 1908, out of what had been previously considered an interesting phenomenon, is essentially as follows:

A gas, or air stream, carrying solids or liquids in suspension, is subjected to the influence of a strong electric field produced by unidirectional current of high potential for the purpose of charging these particles and throwing them out of the gas stream. The gas is passed through the space between suitable electrodes and this space is made part of a high-potential circuit by placing it in series with the high-potential winding of a step-up transformer. Rectification is accomplished by a revolving switch, driven in synchronism, in series with the electrodes and high-potential winding of the transformer. The current is pul-

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sating in character, but this is only incidental as the same results of precipitation may be produced by any source of high potential direct current.

The electrodes are usually referred to as "passive" and "active" since only the cathode serves as a charging electrode. This is effected by making it of relatively small surface compared with the anode so as to make a steep potential gradient near its surface. The passive electrode with its relatively large surface serves as the principle collecting electrode because most of the dust is driven to it. For purposes of safety the anode is made the grounded side of the system.

A few words as to the commonly accepted theoretical conception concerning the manner in which the dust particle is charged and precipitated: This is accomplished through the ionization of the gas which carries the particles in suspension. It is assumed that the negative ion or electron is the ionizing agent and that the velocity of the electron stream is sufficient to ionize the gas molecules by collision in a relatively small zone near the discharge electrode where the potential gradient is steepest. This stream of electrons in making its way toward the opposite electrode is assumed to charge the minute dust particles in passing by contacting or attaching to the particles. The latter having acquired a negative charge, and being in a strong electrostatic field, are attracted by the positive pole and hurled against it with considerable force, where they give up their negative charge to this electrode and cling to it by adhesion.

There are many iinteresting speculations, such as the possibility of some of the particles being charged by electrostatic induction; the effect of the electric wind caused by the electron stream, in aiding precipitation, and the indication and that some of the particles must be charged positively on account of the deposit which is always found on the discharge electrode; but these things are beyond the scope of the paper.

We need not be concerned with the phenomena of just how the particle is charged, but we are with how it may be enabled to give up its charge to the electrodes under all conditions. The inability of the charge to penetrate the insulating coat of dry precipitated fume causes precipitation to cease just as an insulating diaphragm does when placed between the anode and the cathode in an electrolytic cell. The problem in metallurgical work is to overcome this difficulty.

APPLICATION OF THE PROCESS TO SMELTING

In its application to the smelting industry the process differs from other applications in several ways, but especially in the matter of size. Installations are as a rule, based on treating from 100,000 to 1,000,000 cu. ft. per minute. Other installations treating 25,000 cu. ft. per minute, such as at brass foundries and detinning plants, are considered a good size. Another important difference is the varying conductivity of smelter gas as compared with other gases. The matter so precipitated varies from a dry basic fume or dust to one containing enough dilute sulphuric acid to make it difficult to remove the deposit from the electrodes.

Electric precipitation was used primarily for the purpose of abating a nuisance by preventing solids from the smelter stacks being carried to the surrounding fields. A greater usefulness was soon found for it in recovering these solids for the values therein.

Twenty-five years ago in the copper smelting industry comparatively little attention was paid to recovering the solids driven off with the gases from the furnaces. The first attempt was made by building longer flue chambers to recover what might be settled out by gravitation and by adherence to the walls. As the industry increased more attention was paid to the very considerable dust losses and these flues were widened considerably for a length of 100 ft. or more to reduce the gas velocity, thereby causing considerable of the heavier suspended solids to drop out. During this time, and in fact prior to it, the system of filtering the gas through woolen bags for the purpose of reclaiming these solids, was in use in lead smelting. This method could not be applied very well to copper smelting due to the fact that the gases were much hotter and usually carried considerable sulphuric acid, these conditions contributing to the rapid deterioration of the bags. At one copper smelter, however, a bag-house was successfully operated by causing the heat from the gases to radiate from a long series of iron pipes, all the free acid being neutralized before reaching the bags by the large amount of zinc oxide present.

The principal disadvantages of bag-houses are the high first cost, together with the maintenance cost of bag renewals, and the very considerable cost of power rquired for forcing the gases through the bags and for producing mechanical draft.

While the long brick settling chambers were quite expensive, especially if equipped with hoppers, they constituted the only practical method of reclaiming the dust lost from copper smelters until the advent of the Cottrell process. Even then it was for a long time considered only an adjunct to the settling chamber. Until recently many of those best informed considered that the process was applicable exclusively to the field where the gases carried enough sulphuric acid, due to the sulphur in the charge, to render them conductive, and that all dry gases could be treated only by the bag-house. As will be shown later, the process is now being extended to dry gases also, by means of conditioning such gases.

Although quite expensive when constructed of steel pipes with hoppers and header flues, the Cottrell plant proved to be a very good investment on account of the large amount of solids recovered which would not settle out by gravity. One serious drawback to this type of treater, which limited its application, was the inevitable loss of draft, partly due to cooling the gases in passing through these pipes but principally due to the loss in velocity head in passing the gas around so many extra right-angle bends.

Due to recent improvements in treater design smelter construction has been revolutionized by the Cottrell process. Almost any kind of gas can now be treated and long settling chambers are no longer necessary. The chimney may be erected comparatively close to the furnaces and connected with them by a short length of chamber equipped with electrodes which recover all that the long chambers formerly caught plus the larger amount which passed them. This can be done with practically no loss in draft.

TREATER DESIGN

The original treater consisted of a tank through which the gas was passed horizontally. The positive electrodes consisted of narrow lead plates placed vertically and edgewise to the gas current. Adjacent rows were staggered with reference to each other. Midway between each pair of plates and insulated from them were hung the negative discharge electrodes, which consisted of lead rods to which were clamped strips of micanite with saw-tooth edges. Later iron was used for both sets of electrodes where the gas to be treated carried little acid.

The pipe treater was developed in 1911 and has been used extensively since. In this treater the gas is bypassed from the main flue through vertical iron pipes from 10 to 15 ft. long and then returned to the flue where it passes on out the chimney. Iron wires of about No. 14 gage, supported by an insulated frame, are stretched through the axis of these pipes and serve as negative or discharge electrodes. Most of the dust is precipitated on the inner surface of the pipes and is shaken from them into the hopper below by rapping the pipes after the flow of gas through them has been interrupted.

Somewhat similar to this in principal is the box treater, in which the pipes were replaced by vertical corrugated iron walls horizontal to the gas flow. Vertical chains or wires were suspended between these walls and were insulated in a similar manner as in the pipe treater.

The idea of using the corrugated iron walls was later used to better advantage by causing the gas to flow between them horizontally instead of vertically. This permitted installing them in a settling chamber already erected, and being a straight-line treater, the walls could be carried any desired length, whereas in the box treater the height of the walls was limited for structural reasons. In this installation the discharge electrodes consisted of ⅜-in. iron pipes suspended parallel to the gas flow midway between the walls. Such a large surface does not permit steep enough potential gradient for the efficient ionization of the gas.

A short time previous to the development of the straight-line treater just discussed another type of straight-line treater was developed, which is known as the "screen treater." The object desired in this treater is to apply the principal of ionizing the gas in the most efficient manner and thereby reduce the power consumed, which is the principal fixed cost of a large plant. Probably more important than this to the plant manager is the very considerable reduction in first cost on account of the fact that chambers already in existence can be utilized and that in its construction a minimum of material and labor are required. Since these things have been accomplished so successfully on a large scale both in this type and in its successor known as the "wire treater," which is really a simplified screen treater, it seems worthy of some discussion from theoretical and practical standpoints.

In the pipe treater and various kinds of plate treaters, it is evident that the potential gradient is steep enough to ionize the gas only in a comparatively small area near the surface of the discharge electrode permitting a path of relatively large area near the walls of the pipe or plates through which the gas can flow in a straight line in a very weak electric field. In one large pipe treater installation in order to obviate this difficulty and get as high a degree of cleaning of the gas as possible, the gas was passed through three separate plants in series, the mixing action in passing from one plant to the other serving to give all the gas a better chance of being ionized. It was not practicable to increase the length of the pipes in one plant sufficiently to accomplish the same result on account of the amplitude of the swing of the discharge wires in the pipes becoming too great, due to the corona discharge. While this arrangement proved successful it was quite expensive from operating and first cost standpoints. It is quite evident that the same result as obtained with treaters in series can be obtained by putting vertically hung electrodes in series in the same chamber and having the gas flow parallel to the electrostatic discharge instead of at right angles to it as it does in all other types. In order to accomplish this in the best manner the gas must flow through the planes of the passive electrode instead of between them, which is only possible if the passive electrode is in the nature of a screen. Accordingly the treater was constructed by placing a series of parallel screens across a chamber. The discharge electrode consisted of vertical wires supported by an insulated structure and stretched between the pairs of screens. It is evident that these pairs of screens with their discharge wires function as treaters in series. Since the wires in each row are staggered with reference to the other rows, no single gas molecule can find its way through even a short series of these screens without passing close to a discharge wire and through a field sufficiently intense for its ionization. The reason for the relatively small cost of such an arrangement is obvious and requires no discussion. As to its economy of power used, this may be better understood by comparing a screen treater with any other type, say a pipe treater, each having its electrode surfaces proportioned so that the same watts will be consumed in the two treaters, discharging in air. With the same volume of gas flowing through each, but an excess over the current amount, it is evident that the screen treater will precipitate the most dust on account of the more efficient ionizing of the gas for the power expended; therefore there are less watts consumed per unit weight of dust recovered. Having a minimum amount of surface exposed where radiation can take place, the temperature of the gas is conserved, and having no extra bends, the drop in draft is reduced to a minimum. The drop in draft across such a treater, cleaning gas at a 10-ft.-per-sec. velocity, rarely exceeds 0.1 inch of water and in no case has the precipitate on the screens interfered with operation, regardless of the sticky condition produced by acid. Draft is all important to the smelting man who finds more often than not, that a reduced draft means less ore tonnage smelted. Minimum draft loss is one of the features of this wire treater. Another important advantage is that there are no insulators exposed to the gas with the inevitable current leakage over their surfaces. The insulated structure is suspended at the four corners by members passing through holes in the cover plate. These holes are sealed by insulating lime seals in which crushed burnt lime, which has a high dielectric constant, acts so as to neutralize any acid which may condense on it and at the same time preserve a high dielectric strength. A feature worth noting is the fact that in this type of treater the gas stream always carries any dust that may be blown off toward a collecting electrode. Another advantage is the ease of shaking dust from a small or broken surface as compared to a solid surface.

The wire treater embodies all of the advantages of the screen treater plus the very distinct one of a greatly simplified construction with a much reduced first cost. In effect it amounts to electrifying a small portion of the wires formerly hung in a dust chamber for the purpose of knocking down the small amount of dust which might adhere to them mechanically. As in the screen treater, the length of the treater can be increased at will to obtain any desired degree of cleaning. The amount of dust caught over the length of the treater varies in the form of a logarithmic curve, half of the total being caught in a relatively short length making a very high return on the first portion of the investment. From this it is obvious that a large part of the solids in a gas can be recovered by installing a relatively short section of the treater, the length depending on the degree of clearance desired. In practise it has been found that a treater length of 20 ft. having an active or ionizing length of 10 ft. is sufficient to precipitate practically all the solids from gases flowing at the rate of from 10 to 12 ft. per second.

METALLURGICAL CONSIDERATIONS

In reference to the metallurgy of copper and lead, this paper is concerned principally with the conditions affecting the amount of water vapor and sulphuric acid in the gases from the various metallurgical units, and with the nature of the solids which the gases carry. It is on these things that the successful operation of the Cottrell plant depends.

As a rule these metals exist in their ores combined with sulphur, although there are some large oxide deposits. Before these ores can be smelted it is necessary to roast off a large amount of this sulphur. This is usually accomplished by multiple hearth roasters in which the ore is fed at the top hearth and is passed down through the succeeding hearths, being stirred or rabbled in transit. The sulphur in the ore usually furnishes the heat for its own roasting, although auxiliary heat is sometimes supplied. The gases from such roasters used for driving off excess sulphur contain more sulphuric acid than the gases from any other metallurgical unit. This acid is caused by the large amount of sulphur dioxide driven off and the fact that in passing up through the various hearths it has considerable contact with whatever catalysts may be present, such as iron oxide. The sulphur trioxide thus formed unites with the water vapor present in the gas and makes sulphuric acid.

There is another type of roaster in common use. It is a straight line roaster in which the fine ore is placed in thin beds on pallets which are drawn slowly through a short fire-box, this action serving to expel a large amount of the sulphur and at the same time to sinter or agglomerate the charge. The gas from this roaster contains very little acid on account of the short time of contact of the gas with the material at the proper temperature as it passes through the thin bed on the pallet. About the only thing contributing to making this gas treatable is the fact that in order to be agglomerated the charge must contain considerable water, often as much as 10 per cent. This water then furnishes enough conductivity to afford precipitation if the temperature is low enough to permit sufficient relative humidity to obtain.

In the case of copper, the roasted material, now known as "calcines", is then dumped into a large reverberatory furnace heated with powdered coal or oil. This type of furnace is quite similar to an open-hearth furnace, the gases leaving it being extremely hot. A large part of the sulphur remaining in the charge unites with the iron and copper in about equal parts to form a physical mixture known as "matte." This is separated from the slag by settling. The gas from this furnace contains very little SO_2 from which conversion to acid is obtained by coming into contact with whatever catalizer may be present on the side walls. In addition, the gas is very hot and there is practically no water in the charge, it being driven off by the roasting. These conditions make it an exceedingly difficult gas to treat.

Sometimes blast furnaces are used instead of reverberatory furnaces. This is often the case if the ore is in large lumps. The same disadvantages apply to treating these gases with the added disadvantage of a wide temperature variation. This temperature variation depends largely on whether the furnaces happen to be operating with a cold or a hot top.

From the furnace the matte is poured into a converter, which is a relatively small cylindrical furnace, and is rotated on trunions for skimming off the slag. Air is forced in at the bottom and, passing up through the bath, oxidizes the sulphur combined with iron first, on account of the higher affinity of oxygen for such sulphur. Slag is produced by adding silica, and as it rises to the top is skimmed off periodically until only the combined sulphur and copper, known as "white metal" remains. During this slagging period very little acid is made which is available in the treater, and what acid is formed in the gases reacts with the oxides present, and the sulphates formed are not precipitated more readily than the oxides or sulphides of the original charge. The gas from a converter in the slagging stage is perhaps the most difficult of all to treat, as it contains no acid and practically all of the suspended solids are present in the form of fume, that is, material which has been condensed from a volatile state. During the second stage of converting, considerable acid is made due to the oxidizing of the sulphur, and conditions are favorable for good precipitation If there are several converters operating it is well to have their stages arranged so as to have at least one of them on the finishing stage all the time.

While the discussion has been confined principally to copper, the metallurgy of lead is so nearly similar that for our purpose little distinction need be made. It should be pointed out, however, that in lead smelting the reverberatory furnaces are not used, and that the lead is made without the use of converters it being smelted directly in the blast furnace where a reducing atmosphere is maintained.

The suspended solids from these various metallurgical units are sulphides, sulphates and oxides; however, the chemical nature of these solids does not seem to enter into the matter of their precipitation. Their physical nature is all important. It is a comparatively easy matter to precipitate flue dust, that is, material which has not been condensed from a volatile state. Frequently some of the material just as it is charged is present in the gas. This is especially true in the case of the multiple hearth roasters in which the constant stirring causes a considerable amount of the fine particles of the charge to be carried out with the gas currents. The wide application of the flotation process has contributed greatly to this dust loss from the charge, on account of the exceeding fineness of the particles. In fact, if it were not for the Cottrell process the flotation process would not be as great a success as it is, because of these losses.

There are several theories as to why fume does not readily lend itself to precipitation. Of these theories the one usually advanced is that on account of the exceedingly small mass of the particle it is not able to acquire enough electric charge, or enough momentum with the charge it does acquire, to cause it to lodge on a collecting electrode before it is swept by. This theory would seem to be disproved by the fact that these fume particles actually are charged and migrate to the electrode, but experience difficulty in giving up their charge to the electrode after the latter has become covered with a thin coating or film of such material. This is shown by the fact that if a practical method could be devised whereby this film is wiped from the electrodes every few minutes good operation would result. No method of shaking will remove this film sufficiently.

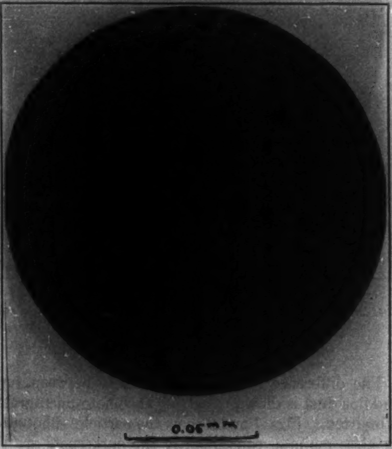

FIG. 1—PHOTO-MICROGRAPH OF CONVERTER FUME MAGNIFIED APPROXIMATELY 560 DIAMETERS

The dark grains are silhouettes of the particles.

There has been some speculation as to the effect of the air occluded in the fume on the electrode. It is a fact that if the fume shaken from the electrodes is beaten or squeezed, enough air will be excluded to make the fume occupy a very much smaller volume than before.

Another theory, which seems the most likely, is that the trouble is due almost entirely to the smooth amorphous state of this coating on the electrodes making it very compact, whereas the flue dust is of a porous nature having small interstices through which the charges may be forced. A good analogy of this is the insulating properties of various kinds of wood. It is known that pine is a relatively poor insulator for high voltages, whereas the same thickness of maple is exceedingly hard to puncture. The difference in the dielectric strength of these two woods is probably due largely to the difference in porosity. A point lending color to this theory is the fact that if flue dust or other rather coarse material is mixed in with the gas and precipitated with the fume it improves the precipitation of the fume.

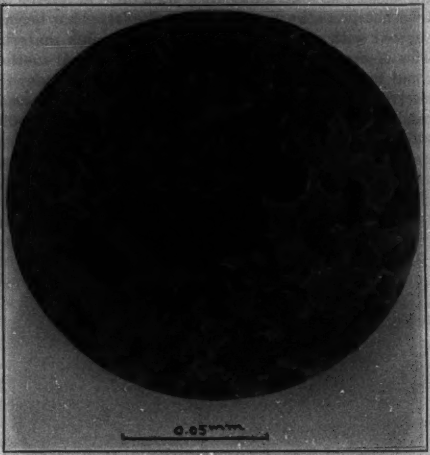

FIG. 2—PHOTO-MICROGRAPH OF ROASTER FLUE DUST MAGNIFIED APPROXIMATELY 560 DIAMETERS

The dark spots are silhouettes of the particles.

The difference in physical structure between fume and flue dust is shown clearly by the photo-micrographs submitted. Figs. 1 and 2 show the particles silhouetted on glass mounts, consequently the dark spots are the grains. Fig. 1 shows the fume particles of high lead content from copper converters which must be conditioned previous to recovery in a Cottrell plant. Fig. 2 shows fine flue dust recovered from roasters which lends itself to treatment very well without conditioning in spite of the fact that it has a very high dielectric strength. This dust without magnification appears to be a dark powder of fineness comparable to that of the fume but when thet wo are magnified approximately 560 diameters, as shown, each particle of flue dust is shown to be about 20 times larger than the fume particle. These flue dust particles are also shown to be irregular in form with rough edges from which an electric charge can readily leak and pass through the interstices of the coating to the electrode. These sharp edges are further indicated by the wavy lines which are pictures of minute spectra caused by fine edges, similar to diffraction gratings, or crystal clevage planes. The fume particles are seen to be almost spherical in form which fact would make the particle tend to hold its charge.

In Figs. 3, 4, and 5 are shown the compact surfaces of converter fume, roaster flue dust and blast furnace flue dust, just as they were taken from the treaters without any attempt to compress them. The compactness of the fume as shown by its enamel amorphous surface as compared with the granular porous structure of the flue dust is clearly seen. The sample of blast furnace flue dust was taken at a time of excellent precipitation. Under high magnification it resembles a mass of coke. Fig. 6 is a photo-micrograph of chemically pure zinc-oxide which is a true fume and is submitted for purposes of comparison. Its general structure is seen to be quite similar to the converter fume. The areas photographed represent a magnification of approximately 43 diameters.

Laying aside theoretical considerations, the important point is a practical solution of the problem of conditioning gases and this will now be discussed.

CONDITIONING THE GAS

By far the most important consideration in the operation of a plant is keeping the gas and the precipitated coat conductive. Conductivity is a relative term. What is considered a perfect insulator for ordinary voltages and currents may become an excellent conductor where only extremely small currents and high voltages are involved.

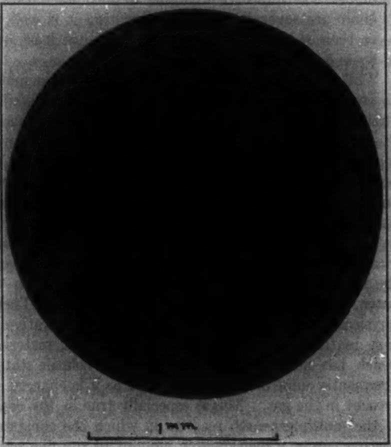

FIG. 3—PHOTO-MICROGRAPH OF SURFACE OF CONVERTER FUME MAGNIFIED APPROXIMATELY 43 DIAMETERS

There are two ways in common use of supplying the necessary conductivity if it does not exist; the addition of sufficient aqueous vapor to the gases, or the addition of very fine acid particles. While the results obtained in each case are the same as regards furnishing

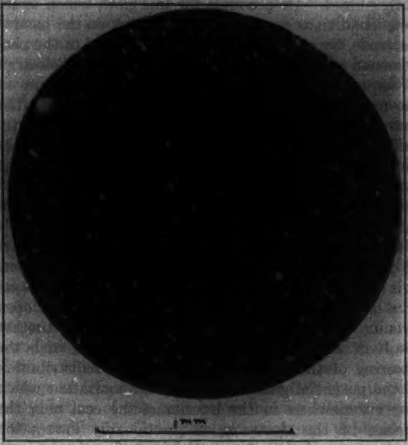

FIG. 4—PHOTO-MICROGRAPH OF SURFACE OF ROASTER FLUE DUST MAGNIFIED APPROXIMATELY 43 DIAMETERS

conductivity for the charge, their methods of functioning are somewhat different.

The selective adsorption theory as an explanation of how relative humidity functions in furnishing conductivity was advanced by the writer in a discussion of a paper presented to the Institute of Mining and Metallurgical Engineers in 1919 by Mr. Eschholz on the subject of "Electrostatic Precipitation." It was pointed out that the dry dust particle must take on a film of moisture, for aqueous vapor is known to be taken up by the surface of solids, and that these adsorbed surface films persist at temperatures far above the boiling point of water. The early work of Bunsen in trying to remove the last traces of moisture from powdered glass or the interior of glass tubes was cited.

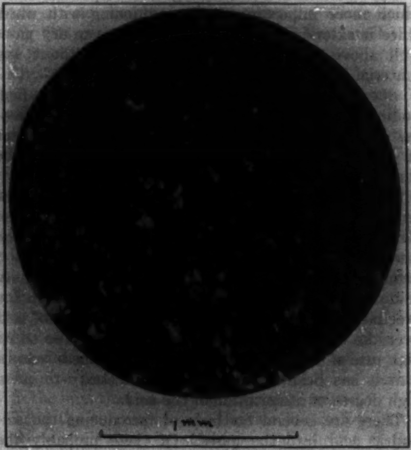

FIG. 5—PHOTO-MICROGRAPH OF SURFACE OF BLAST FURNACE FLUE DUST MAGNIFIED APPROXIMATELY 43 DIAMETERS

If the very slight surface adsorbed film is sufficient to conduct off the charge from the glass plates rendering an influence machine almost inoperative on a humid day, it is not hard to understand why the film adsorbed by dry dust particles from air or gas of like humidity should be sufficient to conduct a charge through the coating to the plate, since the current per unit area is of about the same order as that in the case of the influence machine. As evidence of this 50 milliamperes is a good average current for a treater of 200 pipes six inches in diameter and 12 ft. long. This gives a current density of 0.0135 milliamperes per square foot of electrode area at the pipe. This is to show that aside from the fact that it is a physical impossibility to precipitate droplets of water from a gas below the point of saturation, it is unnecessary, for the aqueous vapor alone is sufficient to conduct off the charge. It has been claimed that the relative humidity itself did not function in conducting away the charge but was only indicative of a condition whereby droplets of water could be precipitated.

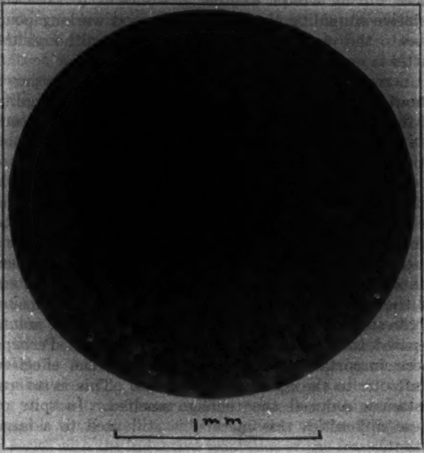

FIG. 6—PHOTO-MICROGRAPH OF SURFACE OF CHEMICALLY PURE ZINC OXIDE SUBMITTED FOR COMPARISON

Increasing the relative humidity of the gas is usually accomplished by spraying into the gas a considerable quantity of finely atomized water by the use of suitable sprays at very high water pressure. Since the relative humidity increases faster and faster with a given moisture content as the temperature is lowered below the boiling point it follows that the water sprayed into the gas is more useful in raising the relative humidity due to its cooling effect than by virtue of the water added to the gas.

From a curve showing percentage by weight of water in saturated air, it is seen that at 100 deg. the percentage of water is only 0.14 per cent. At 120 deg. it is 1.07 per cent, rising with increasing rapidity so that at 150 deg. it is 6.34 per cent.

It is interesting to note that in a large installation operating on roaster gases the cooling effect of the gases during winter weather is sufficient to raise the relative humidity of the gas to a good working point due to the water in the furnace charge, although the latter is not changed in percentage.

As regards the limits for good operation, it was shown about five years ago that when the relative humidity of the gas was kept between 40 per cent and 70 per cent the precipitate would not be too dry or too wet for good work and all other connsiderations, such as temperature could be neglected since the temperature factor is reflected in the relative humidity. This reduced the field that could be covered by water treatment to comparatively cold gases only. Two serious objections to this method quickly developed. It was found that the water caused rapid deterioration of the flue system at the sprays, and the humid gases caused corrosion of the steel of the treater due to condensation at points exposed to the influence of the outside air. Perhaps more important was the reduction of the effective draft due to the cooling of the gases. This in several instances reduced the tonnage smelted. In spite of these difficulties this method is still used to a large extent.

Mr. Wolcott[1] has offered some important theoretical considerations on this matter. In citing the well-known fact that the tendency to arc between a plate and a point is greater when the point is positive than when it is negative, he pointed out that experiments showed the arcing voltage was considerably lowered when the plate is covered by some insulating material. This he did by placing various substances on the plate capable of retaining a charge, such as a sheet of paper or mica. The arcing voltage was lowered still further by a hole in the sheet. A glow was seen to emanate from the edges of the hole. Roughening the surfaces had the same effect. Roaster dust containing a large amount of elemental sulphur, when it was sprinkled on the plate, acted in the same manner. In every case these effects disappear when the dielectric on the plate was dampened very slightly or when the atmosphere was quite humid. He accounts for this glow, which under some conditions can be seen in the dark on the passive electrode, by theory of back ionization, and to the phenomenon produced by discontinuous unlike dielectrics in series which in this case are the dust particles in the coat and air in the interstices between them. The charge, which is retained by these particles, is evidently sufficient to ionize the gas adjacent to them. Since the sign of this charge is negative like that on the particles migrating to the passive electrode, the latter will be repelled, somewhat, by the dust already precipitated.

It seems, however, that these phenomena are results of precipitation having ceased, and not the causes. It is evident that the moment the particles can no longer give up their charge it becomes equivalent to an open circuit. We may be concerned more with another result of this back ionization than we are with the lowering of the sparking voltage. The redistribution of the potential gradient, due to the ionization which starts somewhere in the interior of the coat near the surface of the electrode, unquestionably lowers the gradient at the discharge electrode by the amount gained by the passive electrode. In this way it differs from the ideal distribution of the voltage, in which its gradient is as steep as possible near the surface of the discharge electrode, and quite flat at the passive. This is similar to a case cited by Dr. Whitehead in which he found that the corona glow at the wire almost disappeared when an intermediate concentric tube was inserted between it and the outer tube due to the accumulation of ions in the intermediate tube lowering the gradient at the wire.[2]

The method of conditioning with sulphuric acid is much more important than conditioning with water since it extends the scope of the process to dry gases well above the boiling point of water without any material lowering of the temperature and draft. This is due to three of its properties; its relatively high boiling point; its power to absorb water from surrounding gases at temperatures well above the boiling point of water; and to its rapid rate of diffusion over the surface of solids.

Since it remains in a liquid form at ordinary gas temperatures it is evident that the phenomena of selective surface adsorption does not occur as it does in the case of the aqueous vapor. It is more likely that it furnishes its conductivity by being precipitated as minute acid droplets which are well disseminated through the precipitated coating and quickly spreads a film of acid over the surface of adjacent dust particles due to its high rate of diffusion. Probably it is for these reasons that it has been found absolutely necessary to get a high degree of atomization of the acid.

There are several methods of introducing the sulphuric acid into the gases. Of these probably the better is to fume it off by boiling the acid and introducing the mist into the gases at some point in the flue system where it may become well mixed through the gases before reaching the treater. In one instance the intense heat of the copper converters was taken advantage of for the purpose of conditioning the gases, by introducing the acid at the hood of the converter by means of a spray. The intense heat atomizes the acid to the highest degree. The advantages of this fine dissemination of the acid probably more than offsets the disadvantage caused by cooling the gases from approximately 1000 deg. cent at the converter hood to 150 deg. cent. at the treater, resulting in considerable acid lost in forming sulphates since time is afforded for the reaction at suitable temperatures.

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[1] "Effects of Dielectrics on Sparking Voltage," by E. R. Wolcott, *Physical Review*, N. S. Vol. XII, No. 4, Oct. 1918.

[2] "Electric Strength of Air," Whitehead and Brown, A. I. E. E. TRANSACTIONS, Vol. 36, 1917.

Another method consists of breaking up the acid into a very fine mist by high pressure air sprays and introducing it at a point near the treater so that all of the acid may be available in a free state. One advantage of this method is due to the fact that it permits dilution of the acid before mixing with the gas when required. Concentrated sulphuric acid is a very poor conductor of electricity. It becomes more highly dissociated and hence more conductive electrically as it approaches a concentration of 30 per cent. It is hard to precipitate a very dry mist, such as that fumed off by boiling, unless it has an opportunity of diluting itself by coming in contact with air containing appreciable moisture. In cases where there is practically no moisture in the gas the acid introduced may all be made available in the treater by diluting it before spraying into the gases, at the same time furnishing a greater volume of liquid at a higher degree of conductivity with which to condition the particle. This result can not be obtained in boiling the dilute acid, for in this case the water is driven off first until the acid reaches a high concentration.

Another method of conditioning which conserves the acid is known as "conditioning the electrodes." Good precipitation may be secured from gases carrying a dry basic fume by spraying the interior of the pipe electrodes with a fine mist of sulphuric acid intermittently. The periods between applications vary from one to twenty-four hours, depending on the nature and amount of suspended solids. If there is present much zinc oxide or other material which will quickly take up the acid, more frequent applications are necessary. It seems that the acid sprayed on the walls of the pipe adheres to them absorbing water from the gases, spreading a conductive film over the solids as they are precipitated until the supply is exhausted. Better results are obtained when the inner pipe surface is almost imperceptibly dampened with the mist than when it is thoroughly wetted.

Since the success of precipitation in smelter gases depends largely on the sulphuric acid content of the latter it may be interesting to note just what constitutes the right amount for good working conditions. Data were taken over a considerable period of time to establish this during the operation of a plant securing good results without conditioning the gases. With an average gas volume entering the treater of 470,000 cubic feet per minute at 184 deg. cent. of mixed converter, roaster and furnace gases, the precipitation over the period as noted visually varied from poor to excellent with the sulphuric acid content of the gases, and filtration tests showing that 67.7 per cent of the solids entering the plant over the entire period had been recovered. The average SO_3 entering the treater during this period was 4.9 g. per 1000 cu. ft. of gas (standard conditions), which is equivalent to 6 g. of H_2SO_4. Leaving the treater, there were 3.1 g. SO_3 or 4 g. H_2SO_4, showing that 33 per cent of the acid was precipitated. This gave a free acid content in the dust precipitated of around 1 per cent. A good working rule is, that gas lends itself to treatment readily if it contains enough acid to give a free acid content in the dust recovered of from 1 per cent to 5 per cent. With greater acidity the dust becomes sticky making it difficult to remove the precipitate. It also causes a high treater current and low treater voltage, which means high power consumption with poor precipitation.

ELECTRICAL CONSIDERATIONS

There was an early tendency to attribute the frequent fluctuations or erratic behavior of the plant to various electrical phenomena, especially when it was repeatedly seen to accompany poor precipitation. An example of this is when the dryness of the precipitate on the electrodes increases the electrostatic capacity of the treater sufficiently to cause a resonant condition which is manifest in sparking across the protective gap between the terminals of the high potential winding of the transformer. This critical combination is possible since the capacity reactance of the treater is in series with the inductive reactance of the transformer during a portion of each cycle. That the low treater voltage that this necessitates in an effect and not a cause of the poor precipitation, is shown by the fact that when the electrical system is rebalanced by juggling the inductive reactance of the system so that the treater voltage can be forced up to its value for good work, poor clearing of the gases still continues. When the gases are humidified sufficiently the surging condition disappears and good precipitation results, which continues fairly good when the voltage is lowered down to where it was with the resonant condition. The good precipitation was the result of conditioning the dust particle so that it could give up its charge rather than to reducing the surges. The effect of humidifying the gases in reducing the surges is shown quite clearly by the oscillograms in Fig. 7, where the transient in the high-potential wave at the point the contact is broken is seen when the gases were dry to be about three quarters the root-mean-square value. When they were humidified, this surge is seen to be greatly reduced. During this test, only one half of each wave was utilized for purposes of safety to the oscillograph. It is interesting to note in this connection that lowering the frequency of the impulses in the treater one-half in this manner has no effect on precipitation except as it lowers the resulting treater potential, and this can be partly compensated for by raising the primary voltage a corresponding amount. There are conditions where the power consumption can be cut almost in half in this manner with only a slight diminution in precipitation. As a rule though the values in the dust lost in this way more than offsets the cost of the extra power.

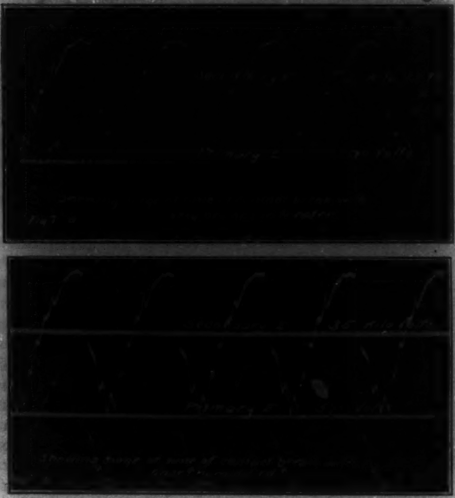

Fig. 7—Oscillograms Showing the Effect on the Surge in the High Potential Wave of Humidifying the Gases

Some of the early generators developed for precipitation work had rather a poor wave form, probably due to tooth ripples. These harmonics had a tendency to increase the effect of the surges and consequently this small defect frequently came in for a good share of the blame for poor work. As a matter of fact, when the gas is in good condition for treatment no difference can be observed in the precipitation from what it is with a perfect sine wave.

There has been considerable discussion as to the best transformer internal reactance. Off-hand one would say that a transformer of high internal reactance is best for the same reason that it is in electric furnace work, so that it can carry a short circuit, which frequently occurs in the treater, without injury. But this is not a real consideration since the revolving contact of the rectifier does not permit a very large current to flow into the treater even on short circuit. Standard power transformers have proved quite satisfactory. One reason for this seems to be that the greater the reactance the more the crest voltage of the wave will be lowered during the portion of the cycle that the rectifier connects the transformer to the treater, making a steeper wave front at time of contact and increasing the surging effects. This lowering of the crest voltage is shown by the oscillogram of the primary voltage wave in Fig. 8. The writer has frequently found that the tendency to surge was reduced by connecting to such a tap in the low-voltage winding as will give a maximum number of turns in series with a corresponding increase in the impressed voltage.

It is now pretty well understood that the electrical side of the process is of less importance than the treater and gas conditions. There is a saying among operating men "get the gas right and electrical troubles may be forgotten." That is the real problem. Electrical matters are relatively unimportant except as they effect the voltage and current of the treater. All that can be required of the electrical system is to stress up the space between electrodes to the economical limit, regardless of the source of the power, the number of electrical sets, or the type of electrical equipment comprising them. As to the current values, it is evident that with a given voltage impressed on the electrodes of a treater the current depends entirely on the conductivity of the space between electrodes and takes care of itself. At least there appears to be no method of varying it except to vary the conductivity of this space by changing the nature of the gas.

There has always been a good deal of uncertainty among engineers regarding the correct number of electrical sets to use for a given treater installation, or, putting it another way, the best proportioning of the investment. There has been a tendency to follow the lead of some other plant without determining if that proportion was best suited for their particular conditions.

Fig. 8—Oscillogram showing the Time of Rectifier Contact to Primary Voltage Wave, the Treater Voltage Wave, and the Current Wave Impressed on the Treater

Since the main function of the electrical equipment is to keep adequate electrode potential, the investment for any equipment over this is wasted. The curve representing treater voltage, which may be taken as per cent precipitation as obtained from a single set, falls off rather fast beyond a certain limit as the number of electrodes is increased and then flattens out at about 50 per cent of maximum voltage. The problem is to determine the economical limit on this curve, *i. e.*, to obtain the most satisfactory balance between the cost of extra machines and power consumed against the extra dust recovered. Since the values in the dust differ at different plants and the rate the treater voltage falls off differs with different types of precipitate, it is evident that no general rule can be laid down and that local conditions should govern. An economic limit for average conditions on a pipe treater was found to be 200 pipes, 12 ft. long and 6 in. diameter per electrical set, but it should be pointed out that with the pipe treater the electrical set only comprises from 10 per cent to 15 per cent of the investment so that an increase of 25 per cent in the number of machines used did not add a large per cent to the total investment. A new complexion has been placed on this matter by the fact that in the more modern wire treaters the treater plant has been cheapened so much that the electrical investment is now as great as the treater investment, which has a tendency to increase the number of electrodes per set.

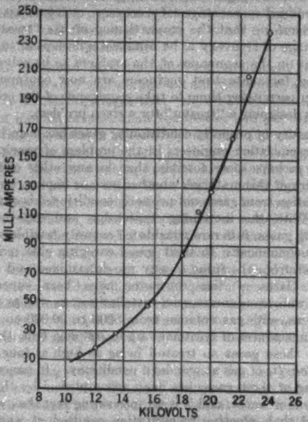

FIG. 9—SHOWING CURRENT AND VOLTAGE RELATIONS ON WIRE TREATER AS VOLTAGE IS INCREASED

Electrical sets of 15 kw. capacity have come to be regarded as standard for precipitation work. This is due largely to the rectifier having a poor regulation. The drop in rectified voltage becomes considerable if it is attempted to pass much more than half an ampere over the revolving contacts of the rectifier. The transformer as a rule steps up from 440 volts to 22,000 and 44,000 with intermediate taps. This is suitable for the electrode spacing of six inches usually employed where an electrode potential of 25 kv. is adequate. However 12 in. spacing has been used somewhat, requiring voltage values of twice those given.

Mr. Eschholz has shown in his paper[3] that although the voltage is impressed on the treater in impulses, it has the effect of that from any continuous current source, due to the electrostatic capacity of the treater filling up the spaces between. This fact was established quite early by means of oscillograms (See Fig. 8 in which treater voltage and current waves are shown).

An important point not usually recognized is that due to the cumulative ionizing of the gases as the voltage is raised above a certain limit (explained by Townsends' theory of ionizing by collision) causes the circuit to become more and more conductive so that the last few thousand volts impressed on the electrodes is at the expense of greatly increasing the current flow and hence the power consumed. This is shown very clearly in Fig. 9. While this is a curve showing the current and voltage relations on a wire treater, it may be taken as typical of other types and follows very closely Mr. Peek's curve showing corona loss[4] near the critical voltage for large conductors. In the case in question it is seen that by increasing the voltage from 22 to 24 kv. the kilowatts consumed increased 43 per cent, a useless waste of power since the gases were cleared in this case almost completely at 22 kv. It is evident that considerable power may be wasted if the gases are in a good condition for treatment if the commonly accepted rule of carrying the treater voltage as high as possible is observed. This is a good rule to follow, however, if the gases are so non-conductive that adequate current cannot flow.

It is just as important to know the treater voltage and current values in a Cottrell treater as it is to know the cathode current density and cell potential in electrolytic work, and the best way of obtaining these is to connect a milliammeter in series with the ground side of the treater circuit and to connect a dead beat electrostatic voltmeter which reads root-mean-square values across the electrodes. While the readings obtained may be out a small percentage owing to the intermittent flow of current into the treater, they are at least comparable with each other and serve all practical purposes. It is misleading to try to calculate the treater voltage by multiplying the voltage across the low-tension winding by the ratio of the transformer, on account of the changing ratio of alternating current to direct current at the rectifier with varying conditions. It is also often misleading to use the value of the current flowing in the low-tension winding at different times for comparative purposes, on account of the power factor changing with the nature of the gas in the treater.

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[3] "Electrostatic Precipitation," O. H. E. Eschholz, Vol. LX, American Inst. Mining and Metallurgical Engineers *Transactions*.

[4] "Dielectric Phenomena in High Voltage Engineering," F. W. Peek, page 144.

As already intimated, the various types of electrical equipment used have received more than their share of consideration. For a time it seemed from the attention the matter received that the success of the process depended on whether the rectifying switch was driven by a small synchronous motor and the current impressed on the step-up transformer taken from the local power system, or whether it should be mounted on the shaft of a motor-generator, the current driving the motor being taken from the power mains and the single-phase current made by the generator impressed on the step-up transformer. In a discussion of Mr. Eschholz' paper already largely cited on this subject the writer pointed out that it was unfortunate that a non-essential should receive so much consideration and that it was really local conditions which should govern as to which system should be adopted, but pointed out a number of reasons why a large smelting company had found it expedient up to that time to install motor-generator rectifiers.

Acknowledgment is made of the cooperation and assistance of the Salt Lake Intermountain Experimental Station of the United States Bureau of Mines in connection with the photo-micrographic study of flue dust. Especial thanks is due Mr. R. E. Head for making the photo-micrographs, and to Mr. C. G. Maier for advice in their study.

Discussion

DISCUSSION ON "RECENT CONCLUSIONS PERTAINING TO ELECTRICAL PRECIPITATION"* (Schmidt). "ELECTRICAL ENGINEERING FEATURES OF THE ELECTRICAL PRECIPITATION PROCESS"† (Horne), AND "ELECTRICAL PRECIPITATION OF SOLIDS FROM SMELTER GASES"‡ (Rathbun),

Vancouver, B. C., August 11, 1922

C. E. Skinner: It is rather curious that this process, developed primarily to abate a nuisance should become so valuable economically. I have been familiar with some attempts in the Pittsburgh district to abate the smoke nuisance by the Mellen Institute of Industrial Research. They made a smoke survey of Pittsburgh, and a study of this survey shows how desirable it is to abate this nuisance in the Pittsburgh district. However, the values recovered are not such as to justify the cost from the commercial standpoint, and consequently very little has been done.

E. P. Dillon: Mr. Schmidt's paper is very opportune, as it presents clearly an explanation of phenomena which have for many years been an obstacle to precipitation engineers in their efforts successfully to handle certain kinds and conditions of gases that do not lend themselves readily to effective clean-up in Cottrell precipitation treaters.

It is shown that the suspended fume or dust carried in practically any gas may readily be precipitated by proper conditioning of the gas, and while in the case of certain gases there is an apparent anomaly in the relationship between precipitation efficiency and current flow, when such gases are properly conditioned the expected normal relation obtains between precipitation efficiency and current flow.

In substantiation of the theory that a non-conductive deposit on the receiving electrode retards if not entirely stops precipitation, numerous observations have been made, and in a particular instance where the material to be precipitated was ground button dust, it was found that with perfectly clean plates the precipitation was for a short period practically perfect, but after a deposit had collected on the plate precipitation ceased, and in this same problem it was possible, by properly conditioning the gas with the idea of making the deposit conducting, to maintain continuous precipitation.

Mr. Schmidt's analysis of the economics of "treater" design is extremely important, since it is the engineer's function to so design and proportion plants as to show to the user the maximum return on the investment, and knowing the conditions, the designer, by Mr. Schmidt's method, may readily so proportion his plant as to accomplish thus result. With the data obtained from wide research and extensive experience now available to engineers, it is possible to design "treaters" for practically any problems of cleaning gas that will in practical operation obtain a predetermined percentage of recovery or clean-up. It is obvious, therefore, that the proportioning of the "treater" for the percentage of recovery to be obtained will depend to a very large extent on the economics of the problem to be solved, and it is indeed fortunate that engineers are now equipped with information permitting them to take cognizance of the economic elements in designing a "treater" for a given problem.

The necessity of properly conditioning gases has been brought home to precipitation engineers in the problem of precipitating zinc oxide perhaps more forcibly than in any other operation. The recovery of this material, whether pure or impure, by means of precipitation from gases not properly conditioned is extremely difficult. With the increasing knowledge and experience of conditioning gases, it is now considered entirely feasible successfully and economically to treat gases carrying zinc oxide, removing therefrom the fume at any pre-determined and desired efficiency. Gases of this character have been successfully handled in numerous commercial installations, as well as various test problems, with gas volumes from 5000 to 20,000 cu. ft. per min. at temperatures of treatment up to 700 deg. fahr. the fume content of these gases so treated being as high as four to five grains per cu. ft. of gas at standard conditions. In general, the conditioning of these gases has been accomplished by the addition of steam or water, and it is an interesting fact that when so conditioned that effective precipitation resulted, it was found that the precipitate was in a dry form, as required for commercial conditions.

In most of the earlier electrical precipitation installations the treaters were of the open type discharging into the atmosphere, or if closed were so designed merely for the purpose of conducting the gases to stacks. Recent developments, however, have brought about designs of gas tight treaters where the gas is used after being cleaned in the treater, and such gas tight "treaters" have been used in some instances for the cleaning of explosive gases. Numerous installations of the gas tight treaters are now in commercial operation, giving very satisfactory results and evidencing material progress in applying electrical precipitation to an ever widening field of gas cleaning.

Referring to Mr. Rathbun's paper. In the earlier stages of the practical application of the electrical precipitation processes they were considered applicable only to the recovery of sulphuric acid mist, and, as Mr. Rathbun states, for some time later they were thought of as a means only for abating a nuisance. The variety of the applications of the processes to gas cleaning problems has extended to such a point that now practically any fume or dust recovery problem is susceptible of solution by these processes. In fact, the metallurgist and chemist is now free to develop processes disregarding fume losses, even going so far as to create fume losses in process operations, since the Cottrell processes may be relied upon for efficient economical recovery of such losses.

The description of the wire type "treater" is extremely interesting, particularly in view of the fact that it is based on actual experience, and it is undoubtedly a valuable contribution to the subject of precipitation. Draft losses are an ever present problem to the precipitation engineer, and constant efforts are being directed to minimize such losses in modern designs. Modern installations are so designed that the draft losses will not exceed 0.25 in., and in a wide variety of installations it is found that the draft loss is much less than this, ranging from 0.15 in. to 0.10 in.

The presence of sulphuric acid in some form in the gas is certainly a great aid to precipitation, and the idea suggested by Mr. Rathbun of adding sulphuric acid by various methods to the gases, with the attendant favorable results, indicates a material advance in the art of precipitation. In many plants, however, sulphuric acid is not available for such use, and it has been found in a wide variety of operations that eminently satisfactory conditioning of the gases can be obtained by the proper introduction of water or steam, and this result has been obtained in numerous instances with gases at high temperatures of treatment with a resulting dry precipitate, thereby indicating that in some problems at least the use of steam or water for conditioning is not confined to cold gases only.

As Mr. Rathbun says, the electrical equipment for precipitation has been very well worked out and developed, and we agree entirely with the statement that "the electrical side of the process is of less importance than the treater and gas conditioning. In selecting the number of electrical sets for a given installation, there is room for careful thought on the part of the engineer to so proportion the electrical equipment as to insure a reasonable flexibility and at the same time avoid unduly burdening the installation with an increased investment, keeping in mind the necessity, however, of having available a sufficient number of sets to obtain the desired precipitation efficiency. The general trend of treater design seems to indicate a tendency at this time toward the lower voltages. The selection by Mr. Rathbun of 15-kw. sets as standard checks with general practise, although in some smaller installations sets of smaller capacity are used, but it is generally conceded by precipitation engineers that large capacities such as 50 kv-a. or over are not desirable and are rarely if ever used.

The operating voltage of the treater can be predetermined with fair accuracy, but the most effective voltage to be used will vary with changes in gas condition, velocity, etc. and the electrical equipment is so arranged that adjustment of voltage on the treater can readily be made by the operator to obtain best precipitation under existing conditions.

O. H. Eschholz: To the engineer electrostatic precipitation will always serve as an excellent illustration of the successful utilization of advanced scientific knowledge for the development of an important industrial process. While in other electrical systems the presence of corona too frequently is indicative of energy waste or impending failure, in this process it functions as an essential operating agent. Fume, vapor or suspended solids, ionized in the corona surrounding the discharge wire or chain are propelled through an electrostatic field of decreasing potential gradient to finally impinge upon the surface of an adequate receiving electrode. Because of the importance of the corona phenomenon, interest is frequently centered on the character of the treater voltage wave.

On an oscillograph record of treater voltage and current, the peak voltage as measured by sphere gap was 57,000 and the effective voltage, as determined from the oscillogram, was 97 per cent of the peak. The effective mechanical rectifier ground current on this quite large treater was approximately 1 ampere. Numerous oscillograms taken of treater voltage under varying conditions of gas flow and treater capacity gave in most cases effective voltage values exceeding 90 per cent of the peak. This quite flat character of the voltage wave is doubtless responsible for Mr. Horne's observation that the substitution of a high-voltage direct-current generator (Girven) for the mechanical rectifier does not give a substantial increase in precipitation efficiency.

It is of interest to note that the velocity of the charged particles, or heavy ions, is quite low owing to their relatively large mass. This had been estimated[1] for one set of conditions to be of the order of 0.8 in. per sec. Upon disconnecting the supply circuit as a result of this low ion velocity the heater discharge is found comparatively slow. The discharge rate is somewhat greater than would be estimated from the above value of velocity due to the discharge of the treater energy through the oscillograph circuit as well as to the displacement of the ionized gas by the incoming uncharged furnace gases. As a result of the low "ionic drift" considerable energy is stored between electrodes. This energy assists in maintaining treater voltage or serves to quickly reestablish such voltage in the event of a short circuit caused by a break-down between electrodes.

Owing to the slow movement of the charged particles, only those in the immediate path of the arc were discharged, thus permitting the immediate reestablishment of treater voltage when the arc had been ruptured at the contacts of the mechanical rectifier. It is important to note that because of this low ionic drift and the breaker-like action of the mechanical rectifier, the precipitation time lost due to treater shorts is negligible so that it is practicable to operate treaters very close to their critical break-down voltage.

Some consideration should be given to the fact that treater circuits may serve as a source of high-frequency radiations and hence cause "wireless interference." Observations on a small plant have shown that energy stored in the treater proper is radiated from the transmission line, functioning as an antenna, at the natural frequency of the system, as a result of the intermittent corona or arcing occurring in the treater. In the case studied sharp resonance was obtained with the wave meter located at the top of the treater at 150 and 300-meter wave lengths. The sound in the receivers was very similar to the frying noise characteristic of the treater corona. Various expedients may be adopted to reduce the energy of the high-frequency oscillations such as a high resistance in the treater end of the transmission line—a ground wire screen under the antenna—a condenser across treater line and ground at rectifier end or possibly substitution of steel for the usual copper line wire.

J. C. Hale: There are a few points in Mr. Horne's paper which may lead to questioning by those not thoroughly familiar with the subject and it seems desirable to amplify somewhat on certain portions of the paper.

The relative advantages of the synchronous motor and motor-generator set depend largely upon the characteristics of the power supply circuit to which they are to be connected. If the regulation of this circuit is extremely poor it may, as the author has said, be advisable to install a motor-generator set to secure better operation. Sufficiently close voltage regulations to permit entirely satisfactory operation of the present type of synchronous induction motor has been found in practically all the installations which have been made east of the Rocky Mountains. The disadvantage mentioned,—that a synchronous motor requires careful attention on the part of the operator in starting up to secure proper polarity, is in practise unimportant, as the operator can immediately reverse the polarity if necessary by means of the double pole double throw switch shown in the author's wiring diagram, Fig. 1. In most cases the proper polarity can be determined as shown by Mr. Horne in Fig. 5 of the paper. If the wrong polarity is obtained the precipitator will arc over before the voltage can be raised to the proper operating value.

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[1] Electrostatic Precipitation, H. H. Eschholz, *Proc.*, A. I. M. & M. Eng., Vol. 60, p. 243.

The disadvantage that the synchronous motor may slip a pole due to momentary low voltage is, of course, important. Actual tests on the latest design of motors now being furnished by the manufacturers show that they will not drop out of step (or slip a pole) unless the voltage is reduced by somewhat more than 20 per cent. If regulation as poor as this is encountered a motor-generator set certainly should be installed. Such poor voltage regulation is, however, rarely encountered.

With reference to the disadvantages of the motor-generator set, there is a further point which applies especially to small power units, (5, 10 or even 15 kv-a.). It has been shown by oscillographs that unless special attention is given to the generator design the voltage wave obtained from a 5-kv-a. or even a 10 or 15-kv-a. gnerator will be very badly distorted by the oscillations set up by the transformer rectifier circuit. These oscillations are of course too small to react upon the wave shape of a large generator such as would be found on a power circuit. It cannot be definitely said just what is the effect of those wave distortions upon the efficiency obtained in the precipitator. It is obvious however that, if there are very high peak voltages they will prevent, by causing an arc over, the maintaining of a sufficiently high average voltage to secure most efficient precipitation.

With reference to Fig. 6, the reader should be carefully warned not to draw an erroneous conclusion from the curve given. The author's conclusion is unquestionably correct, but it should be borne in mind that although the curve given is typical in shape for all precipitation circuits it will differ in each installation in its location with respect to the coordinates. It might be inferred from the curve given that the maximum obtainable efficiency of precipitation is about 90 per cent. Any desirable location with respect to the abscissa can be obtained by a change in the operation or design of the precipitator unit; in other words, any desired efficiency can be obtained by a suitable precipitator design and there are installations in commercial operation which have shown, by actual test, a continued efficiency of 99½ per cent.

Emphasis should be laid on the reliability of the electrical equipment now available for use in connection with the electrical precipitation process. Eight or ten years ago the objection to the mechanical rectifier because of the high-frequency oscillation set up in the high-tension circuits was very serious and a great many transformer failures occurred. Since that time, by careful study of the problem, the manufacturers of electrical equipment have been able to supply suitably designed and constructed transformers and to protect them by means of external resistance or reactance so that the transformer failures very seldom occur at the present time. All of the other apparatus used in obtaining and controlling high-tension unidirectional currents have been from time to time the subject of study and improvement, and, as a result, thoroughly reliable equipment is now obtainable.

Svend Barfoed: I would like to ask Mr. Schmidt one question: In the treatment of smelter fumes I understand that you can remove SO_3 fumes from the gases, as it is in the nature of a solid. I have not read the paper but I wonder if SO_2, which is a true gas, can be so treated that it also could be removed from the gas so that it will not constitute a nuisance.

W. A. Schmidt: I know of no case where SO_3 has been precipitated as such. SO_3 is very difficult to isolate since it combines very readily with any water vapor present. There is usually sufficient moisture present in the gases to immediately form sulphuric acid which is $H_2 SO_4$. If sufficient sulphuric acid is so formed to exceed the saturation point of the gases at the temperature existing then this excess will form a mist of liquid particles of sulphuric acid and be precipitated as acid or combined with other substances present.

The question of the precipitation of SO_2 has often been raised. SO_2 is a gas and this process does not effect any separation of gases. The suggestion has been made to oxidize SO_2 to SO_3 and convert to sulphuric acid, but that has to date proven impractical.

R. J. C. Wood: It may be of interest to tell about the electrical precipitation that we have been getting on the Big Creek lines. We have a very large precipitator there, 200 miles long and 100 feet wide. We noticed when going over the line some couple of years ago that the aluminum cable was perfectly bright up in the higher altitudes, up near the power houses at the Big Creek end. It looked exactly the same as it did when installed, absolutely new, bright and shining. As you got down into the lower altitudes that brilliancy began to fade, and at two or three thousand feet or so it was of a light brown color. By the time we were down in the San Joaquin Valley it was quite dark brown. By the time we got to Eagle Rock, down near Los Angeles, it was dead black. However, crossing the Tejon Mountains, it lost its color again as it ascended the altitudes—apparently some kind of mountain sickness.

I took a piece of that cable from the Eagle Rock end—and examined it, and I thought at first that this was just discoloration of soot and I could brush it off with my hand. I rubbed it with my hand and I got just a little stain on my hand but the deposit did not come off, and I rubbed harder, and I rubbed until I began to get sore, but still did not remove this coating. All I did was to put a very nice black polish on this coating. The wire looked just like black enamel wire. Finally I got the coating off with either dilute acid or dilute caustic soda. The black powder that came off in the solution I examined under the microscope and found that it was made up of grains of translucent material, I suppose little bits of the country, little bits of rock and dust, and interspersed between those grains were very small black points or spots, but the rather astonishing thing was the transparency of the preparation under the microscope. We expected to see large masses of dark black substance, whereas it looked like a piece of ground glass broken up with just a very few black spots on it.

I am assuming that the voltage on the line causes precipitation of particles flying in the air, that up in the higher altitudes there was not sufficient of the black carbonaceous binder to make the particles stick together, that in the lower altitudes where there was a good deal of oil smoke and so on, the binder cemented the clearer particles together, making a hard coating on the wire. Practically you might say that this coat is a microscopic macadam.

I would like to ask Mr. Schmidt also whether by the use of the treater he could cut part of that very tall stack off. The stack as made—and it is an enormous one, 560 feet high, as I understand—was originally made of that height in order to carry the gases and dust to a sufficient height so that they would not fall on the immediately surrounding country, but be carried off to somebody else. Now, if you put in a precipitator and collect these fumes possibly you might be able to save somewhat in the height of this stack.

W. A. Schmidt: In answer to Mr. Wood's question I would say that in certain cases the stack could undoubtedly be decreased in height, and in fact at some places the stack has been replaced entirely by fans; but in the particular case to which Mr. Wood refers, which is the Anaconda Smelter, that is not true. As a matter of fact, the stack is on the top of a hill, quite a good height above the smelter, and the stack is proportioned so as to give the desired draft behind the furnaces to overcome the resistance in the flue system.

I might say one word in connection with the thought that came to my mind when Mr. Wood spoke of the collection of dust on the high-tension transmission line. As I showed in my informal discussion, the effect of a deposit upon a surface when that deposit is composed of porous or discontinuous dielectric is such as to convert the surface into an ionizing medium. It would be very interesting to obtain some measurements on the high-tension transmission lines on the effect of such deposits on the corona losses. It is quite possible that there might be a distinct effect there.

There is one other question which I would like to touch on in connection with Mr. Rathbun's paper. He speaks of the difference in effectiveness of the wire treater. He unfortunately overlooked pointing out that with the type of construction to which he refers it is possible to put a very large amount of discharge electrode in a very small space. The work which Anderson and Horne conducted, and which is discussed in my paper, shows that after all every treater in its effectiveness follows an exponential equation, and we have no evidence at hand indicating that an arrangement such as Mr. Rathbun refers to in his discussion of the wire treater has any greater effectiveness per unit length of discharge electrode. In fact there is some evidence indicating that the effectiveness per unit length is less. But he does obtain a greater length of discharge electrode with the same cubical contents of the treater, and that, of course, has a distinct bearing upon the cost.

C. N. Beebe: As was pointed out, in Mr. Rathbun's paper, the wire screened treater and also the wire treater were capable of being installed in the present existing flue chamber. It is a fact that modern smelters do not hesitate at all to make an expenditure of millions of dollars on a complete new treater plant; with the wire screen or wire type of treater, which is capable of being installed in the short length of existing flue chamber, the same amount of gases can be treated with the treater, costing three per cent. of a million dollars, or $30,000 approximately. This will give you some idea of the saving to the smelting industry of the research work which Mr. Rathbun has accomplished.

W. A. Schmidt: In connection with that statement I wish to call attention to the fact that in all those cases where the installations have cost sums approximating a million dollars new flues were constructed, and in a measure the entire flue system was scrapped and rebuilt. In the case that Mr. Beebe is referring to, the electrical equipment was on hand, and the cost of installation simply covered the insertion of electrodes into the existing flue.

R. B. Rathbun: The period of six months, which has elapsed since the paper on smelter gases was written, has done much at the various plants at which the author has contact to substantiate the views expressed in the paper on the subjects to "treater design" and "conditioning of the gases."

Discussion of the paper seemed to have centered around the development of the new wire treater described briefly under the head of "Treater Design", together with the other types of treaters.

In view of the remarkable record for construction and operating costs being made at present by this treater in the precipitation field it should require no defense.

Mr. Schmidt remarked in his discussion that it was perhaps unfortunate that the fact was not pointed out that with this type of construction it is possible to put a very large amount of discharge electrode in a small space. The advantage of this is obvious. He does, though, go on to infer that the lessened cost is due to its greater length of discharge with the same cubical contents of treater as in the other types. This would make it appear that its advantages lie almost wholly in its ability to dissipate a large amount of electric power in a small space, whereas it is clearly shown in the paper that economy of power over other types was one of its advantages. It was clearly demonstrated that this, and its high efficiency per unit of cost, was due largely to the fact that it provided a large number of electric fields in series in the same chamber and staggered with reference to each other so that every gas molecule must of necessity pass close to a discharge electrode where the potential gradient is steep enough for its ionization. The fact is again pointed out that in other treaters, such as the pipe, a large portion of the gas passes out parallel to and through the weak field adjacent to the passive electrode which is the wall of the pipe.

In the introduction of the paper it was stated that the subject would be covered from the standpoint of the engineer whose watchword must always be "return on the investment." From this viewpoint it seems immaterial whether or not this treater is covered by the exponential equation developed by Horne and Anderson. It is no doubt a very interesting academic point, however. Nor does it seem important if its superiority measured by the standard of the dollar is conceded whether or not the effectiveness of the discharge per unit of length is less than in other types, as intimated by Mr. Schmidt. This statement, by the way, seems misleading when not qualified. It must be remembered that in the wire treater the gas flow is in the direction of the discharge instead of right angles to it, as in other types, making such a comparison difficult.

It is usual to think in terms of the ionized length, or the distance through which a given gas molecule is in the influence of the electrical field. In the wire treater this length is rather less than in other types for a given gas velocity and cleaning of the gas, having as it usually does only 20 electrified spaces of 6 in. each in series, whereas in pipe treaters the gas usually passes through from 12 to 15 ft. of ionized length.

Mr. Dillon has in his discussion noted one of its very important advantages—that of extremely low draft loss, not to exceed 0.25 in. It might be added that for pipe treaters, performing under like conditions, it is often as much as ½ inch. This conservation of draft is partly due to the fact that the wire treater, equipped with insulating lime seals where live members enter, has practically no infiltration of outside air, but it is mainly due to the fact that the gases are not deflected from their straight course from the furnace to the chimney and suffer practically no interference due to friction of the treater interposed in their direct route.

In regard to Mr. Schmidt's qualifying statement to that made by Mr. Beebe regarding costs. It is true, as the former states, that in the instance cited a large part of the saving was due to the use of flue chambers already in use. In a large sense it was the adaptability of such chambers to this system which led to its development. However, instances have been found where the existing flue does not lend itself readily, and in such cases it is found that a short portion may be rebuilt and the straight line principle maintained without seriously affecting the cost.

Regarding "conditioning the gases." Mr. Dillon, in commenting on present methods as described in my paper, felt that in these considerable progress had been made in the art of precipitation. That is true—but it must be realized that the methods of humidifying or acidifying gases difficult to treat are but makeshifts since the former is injurious to flue and treater system at temperatures where water will condense, and the latter is often prohibitive due to the cost of the acid.

An account of some preliminary microscopic work, together with micro-photographs showing the physical properties of fume and flue dust, was submitted in the paper. It was hoped that this would lead to discussion, or pave the way to constructive thought toward the final solution of this important problem.

Technical Committee Annual Reports, 1921-1922

ELECTRICAL MACHINERY COMMITTEE

To the Board of Directors·

IT has been the aim of the Committee on Electrical Machinery during the past administrative year to extend its usefulness, as heretofore, to a survey of the art through descriptive papers and the arrangement of meetings for their presentation in cooperation with the Meetings and Papers Committee and to assist in the clarification of work in connection with the standardization of temperatures in electrical machinery.

A review of the theory of electrical machinery is opportune from time to time and this Committee has endeavored to follow this idea by inviting a paper on the kinematic reproduction of vector diagrams of induction motors, which was presented by Prof. Karapetoff at the Midwinter Convention. Another paper on "Theoretical Problems in Connection with Induction Motors" was solicited from Mr. B. G. Lamme and was presented at a meeting specially arranged for this purpose at Pittsfield.

The development of large power generating machinery and its application to modern power-house design has been considered in the presentation of important papers on the new development work done at Niagara Falls, on the Canadian side. These papers were presented at the Annual Convention in June, held at Niagara Falls. They describe constructive engineering work of great originality and magnitude.

The problem of the internal heating of coils in alternating current generators, which has been agitated for some considerable time, has received the most careful attention of this committee. At the Pittsfield meeting of the committee held March 16th, the problem itself was fully discussed and it was decided that the designing engineers on the one hand and the operating engineers on the other would present complete experimental data and records at the June Convention. These records were presented by Messrs. Foster, Newbury, and Williamson for the designing engineers, and by Mr. Philip Torchio for the operating engineers.

A most complete discussion of the subject took place, which it is hoped will result in a settlement of this problem by the formulation of rules of standardization, upon which the development work of the art will be based for some time to come.

The efforts of electrical engineers during the past year in connection with the design and construction of electrical machinery have been concentrated very largely upon the subject of greater refinement in the determination of temperatures and upon the development of larger sizes of individual units. This applies particularly to the generators connected to steam turbines and to large water-wheels. The work in the development of the latter, which was so well described by Mr. William M. White in his paper on "Hydraulic Turbine Development" delivered under the auspices of this committee at the June Convention last year, has led to the construction of large hydraulic units at speeds formerly undreamt of. This, of course, was immediately utilized by the electrical engineers for the construction of electric generating units, so that now individual units of capacities of 50,000 kw. are not only being contemplated but actually designed and executed, both for steam turbine connection and water-wheel connection. It is, of course, evident that the latter are very much larger in size on account of their reduced speed.

There is another field in which there is promised great activity and reference is made to the possibilities in the railroad field. It is evident that the condition of the railroads of the country is today such that, unless their present capacity is greatly increased, the railroad system will be unable to do justice to the future of industrial development. It is evident that, through the applications of electrification, the capacity of the terminals, both as regards passenger handling and freight handling, can be enormously increased. This has been shown convincingly in the electrification of the terminels of New York City and Philadelphia, and the sooner the railroads realize the necessity of such work the better it will be for them and for the country at large. Such economic development will naturally carry with it a tremendous stimulus to the entire electrical industry, with the result that the electrical machinery which comes under the scope of this Committee will meet with an area of revival.

The chairman wishes to thank the members of this committee for their active and loyal service rendered failthfully throughout the year.

B. A. BEHREND, *Chairman*

PROTECTIVE DEVICES COMMITTEE

Subcommittee Circuit Breakers and Switches—B. C. JAMIESON, *Chairman*

To the Board of Directors:

Several papers covering certain features of this subject have been presented before the Institute this year, which we feel will be instrumental in improving this type of equipment. The representatives of the Power Club, N. E. L. A. Electric Apparatus Committee, and your committee have cooperated in attempting to clarify interrupting capacity ratings of oil circuit breakers. The three important features in this rating are:

1. The point at which the duty cycle terminates.
2. The condition of the breaker at the end of the duty cycle.
3. The starting point of the duty cycle, whether open or closed position of the breaker.

These points threw this whole matter back to a stage which required discussion of fundamentals supposed to have been thoroughly understood and agreed upon previous to the publishing of the Hewlett-Burnham-Mahoney paper.

A fairly definite understanding has been reached on the first two points, *viz.*

1. Duty cycle terminates with the breaker in the open position.
2. The breaker is to be capable of closing and carrying full rated current.

There has been so much misunderstanding and difference of opinion regarding the third point, that it was decided to submit the subject for general discussion at the A. I. E. E. Annual Convention at the time of the presentation of the papers on circuit breakers. However, when these papers were presented, much disappointment was felt by operating engineers because of the small amount of desirable data that they contained. On this account the discussions were not very fruitful and the matter of duty cycle remained in practically the same undefined state as before. The opinion of your committee, however, is that the duty cycle should begin with the breaker in the open position, and the duty cycle consisting of closing the breaker on a short-circuit and the breaker interrupting this current. The multiple shot rating to be made up on the basis of repeating this cycle the desired number of times.

The committee also favored the suggestion of the manufacturers that the old standard so-called two shot rating be retained as a published or reference standard for the normal measure of breaker capacity.

Until the committee can get further assurance that its findings would receive more approval, it hesitates to submit these findings as a final report. The committee, however, hopes that the ultimate disposition of the matter will be on the basis as recommended since the N. E. L. A. findings are based on a reluctance to disturb existing manufacturing standards. If this is their principal objection it would appear that there is good ground for believing that, with this removed, they would favor the same definition of duty cycle as we propose. Certainly, it would make for a safer and more logical standard of protection to have a breaker which is capable of closing in on a short circuit at its first operation and particularly is this so in view of the fact that in all subsequent operations it must be able to do so.

In view of the lack of agreement among the various organizations interested in this matter of duty cycle, it is proposed that during the coming year your subcommittee shall immediately begin work on a comprehensive plan for the guidance of member companies contemplating oil circuit breaker tests, specifying the data which are necessary to certify or amplify the correctness of the present definition of interrupting capacity of oil circuit breakers. It is believed that such a course will eliminate to a large extent duplication in tests and will also serve to remove elements of doubt as to the efficacy of the tests, either of which would of course result in furthering the development and reducing the hazards incident to the test. It will serve also to accomplish a more thorough diffusion of results among the interested companies and unify the manufacturers in the line of development and progress.

This program would perhaps be a little more logical if it had been possible to dispose of the duty cycle matter during this last year. However, it is believed that the subcommittee will be warranted in going ahead anyway with a more intensive scrutiny of the fundamentals which were assumed as correct in order to get a satisfactory working definition of duty cycle.

Subcommittee on Grounding

E. C. STONE, *Chairman*

The subcommittee on Grounding of Systems of the Protective Devices Committee was created at the meeting of the General Committee held in New York on Friday, Oct. 14, 1921. The scope of the Committee was defined as follows:

"It was decided that a subcommittee should be appointed to study the methods of grounding and collect such information as it thinks desirable regarding the amount of neutral resistance and special application of relays to grounded systems. This subcommittee was to cooperate with the subcommittee on Relays in properly stating the latter phase of this problem."

Under date of November 22, 1921, the subcommittee was further instructed by the Chairman of the General Committee to make a study of the Protective Devices which would be considered necessary in connection with the use of 66,000 volt underground cables for bringing transmission lines of such voltage into the sub-stations.

It was decided that the best method of approach to this study would be a questionnaire. Accordingly, the questionnaire, of which a copy is attached herewith, was prepared. The essential points which the questionnaire was designed to cover are as follows:

General practise with reference to operation.
Grounded or ungrounded.
Number of points grounded.
Method of grounding.
Operating experience.
Switching practise.
Types of grounding resistances.
Inductive inter-action with signal circuits.
Relay systems.
Protective devices other than grounding used to take care of surges.

On account of the unpopularity of questionnaires, it was decided that this one should be sent out only by members of the committee to their personal friends in the various operating companies. The results, however, have been very gratifying and indicate that the men on this subcommittee are in close touch with practically all of the important operating companies in the United States.

It was found that the Electrical Apparatus Committee of the National Electric Light Association was making a study of methods and practise in grounding the neutrals of large generating stations. This study was under the direction of Mr. H. C. Albrecht, who has very kindly cooperated with this subcommittee in every way possible and has made available all of the information which he had collected bearing on the subject.

In collecting the data two major sub-divisions have been made, as follows:

(a) Practise in systems which transmit substantially all of their power at generator voltage.

(b) Practise in systems which step up substantially all of their power to transmission voltages above generator voltage.

In order that this committee might work in close cooperation with the N. E. L. A. committee, Mr. P. H. Chase of Philadelphia was appointed to gather the data and prepare the report on Section A. The report on Section B will be prepared by the chairman of the subcommittee.

Up to the present time, 31 companies have submitted complete answers to the questionnaire sent out. These companies represent a total kv., of 5,002,500 and operate 15,804 miles of transmission lines at voltages from 11,000 up 150,000. Thirteen other companies have submitted the essential facts regarding their grounding practise.

Very wide divergence in practise is indicated. Some systems including many miles of line at very high voltages are apparently operating successfully ungrounded, although the trend is strongly towards a dead grounded neutral for systems operating at 66,000 volts or above. For systems operated at lower voltages, resistances of widely varying ohmic magnitude are used. Practise with reference to switching, type of ground used, and other protective devices is also very divergent and some very unique schemes have come to the committee's notice.

As the collection of data is not yet completed, the report of the subcommittee at this time must be merely a progress report. Because of the wide divergence of present practise, the chairman of your committee feels that the subject is of sufficient interest to warrant holding one or two sessions of one of the main quarterly meetings of the Institute. The data should all be in in time to be presented at any meeting after January 1, 1923. In addition to the report on the data collected on practical operation by the subcommittee, it is also recommended that one or two papers be prepared on the theoretical aspects of the subject. The industry is sadly lacking in definite information as to why transmission systems are grounded or not grounded and what factors determine the method of grounding.

Subcommittee on Lightning Arresters

F. L. Hunt, *Chairman*

The publication of the operating data showing the performance of several types of arresters in a paper by Mr. Roper before the Institute in November, 1919, has apparently acted as a great stimulus to the designers and manufacturers of lightning arresters, as at the present time three new types of arresters are being offered for service tests and there will apparently be at least two additional types offered within another year. In addition the two papers on the subject of Lightning Arrester Protection which were presented at the Midwinter Convention have created considerable interest.

The development of equipment for testing lightning arresters with large capacity, current and steep wave front has been of great help in classifying the different types of arresters as to the relative protective value against surges.

The tests made by this method and the analytical studies of the engineers of the manufacturing companies appear to confirm the prediction from the published data previously mentioned, namely, that a lightning arrester to be most efficient as a protective device, should have a minimum impedance to flow of surge current so as to permit a very high current to flow at the instant of lightning discharge.

These tests also indicate that it is apparently entirely possible to devise an arrester which will have a maximum potential across its terminals that will be less than the primary bushings and the primary windings of line transformers as now constructed for distribution voltages will withstand. It is confidently expected that arresters meeting this requirement will be produced by one or more manufacturers and available for general use within the next few years. When this result is achieved, then disturbances from lightning will be practically eliminated from our low potential distribution circuits, except in the few cases of defective bushings, insulation damaged by severe overloading, or direct lightning strokes. The total difficulties per annum in a large system from these causes should not exceed one tenth of one per cent of the total number of transformers installed.

With the case of the lightning arresters for transmission voltages, the situation is somewhat different. There appears to have been no radical improvement in such arresters during the last few years, but with the development of the new types of arresters for the distribution voltages and with the recent improvements in the methods of testing lightning arresters, and with the large amount of attention being given by the engineers of the manufacturing companies to the analytical study of the subject of lightning and lightning arresters, it seems quite probable that the serious improvement in lightning arresters for distribution voltages now in progress will be followed very quickly by corresponding improvements in lightning arresters for the higher voltages.

A paper read at the Midwinter Convention brought out what the prevailing practise is in the use of lightning arresters on circuits of 10,000 volts and over, and also brought out the fact that some prominent engineers differ widely in their views about the use of arresters from the majority of opinions.

A paper by Mr. Creighton pointed out the operating characteristics of the arresters in use today and their application to the conditions that have to be taken care of on transmission lines, and made clear the fact that apparatus now being supplied under the name of lightning arresters has characteristics so widely different that a need has arisen for a classification of lightning arresters, so-called, as supplied to the operators.

The subcommittee is now working on a classification of lightning arresters which will make possible a more complete comparison of the types available and give operating engineers a better basis for choosing the arresters to be used on their lines. We believe such a classification should include the following sub-divisions:

1. Path of initial discharge.
    (a) No gap in series.
    (b) No resistance in series.
    (c) Gap in series.
    (d) Resistance in series.
2. Rate of discharge at over voltage, normal frequency.
    (a) High rate (specify limits).
    (b) Intermediate rate (specify limits)
    (c) Low rate (specify limits)
3. Rate of discharge at over voltage, high frequency
    (a) High rate (specify limits)
    (b) Intermediate rate (specify limits)
    (c) Low rate (specify limits)
4. Flashover potential at normal frequency.
    (a) 20 per cent (this will include the counter e. m. f. type of arresters)
    (b) Between 20 per cent above normal potential and 1.5 times normal potential plus 5000 volts. (This will include the types of arresters consisting of a number of spark gaps with a resistance in series.)
    (c) More than 1.5 times normal potential plus 5000 volts. (This will include the arresters of the single gap type with resistance in series.)
5. Time required to interrupt dynamic current.
    (a) No dynamic current follows.
    (b) Less than 2 cycles.
    (c) Less than 10 cycles.
    (d) More than 10 cycles.
6. Attention required in service.
    (a) None. (This will include arresters like the most recent designs for low distribution voltages, and contained in a sealed porcelain case that does not permit of inspection or adjustment.)
    (b) Not more than once per season. (This will include some arresters of the wooden box type in which the gaps must be cleaned and perhaps renewed or adjusted.)
    (c) After every heavy discharge.
    (d) Once a day or oftener.

Subcommittee on Current Limiting Reactors

N. L. POLLARD, *Chairman*

Failures. From information gained by the committee from a number of operating companies that use a considerable number of current limiting reactors, it appears that the manufacturers are gradually overcoming many of the weaknesses inherent in previous designs, so that during the past year there were fewer failures. Several of the failures reported were due to the coil supports being too far apart or the coils not being properly braced. The manufacturers have in most cases remedied these defects and it is hoped that the changes made will entirely eliminate this trouble.

A few failures were evidently caused by the thermal capacity being too small for the service. Both the operating companies and the manufacturers are taking the necessary precautions so as to prevent trouble of this nature in the future.

High-Voltage Reactors. One manufacturer reports the new development of a high-voltage reactor which is applicable to high voltage tie lines. The windings are constructed and insulated in a manner similar to transformers and are immersed in oil and contained in steel tanks.

In order to get a straight line volt-ampere characteristic, the iron cores are omitted and to prevent the flux from passing into the tank and causing excessive losses, a short-circuited winding is placed adjacent to the walls of the tank. In water cooled reactors the copper cooling coils are utilized also for the flux shielding winding.

Outdoor Reactors. One manufacturer reports that one of their first outdoor installations was made in 1916. The performance of these and all others subsequently installed has been satisfactory.

During the past year, another manufacturer has started to build outdoor reactors and it is reported that those that have been installed are operating successfully.

Mechanical Strength of Reactors to Withstand Magnetic Forces. One of the manufacturers of reactors reports exhaustive tests both at large power plants and with a 27,000 kv-a. generator specially built for the purpose of testing electrical apparatus under short-circuit conditions. The tests made with the generator were carried up to the point of destruction of the reactors. These tests clearly demonstrated the short-circuit stresses that the reactors were able to withstand.

Use of Shunting Resistors with Reactors. An exhaustive investigation is being made by one manufacturer of the effect of shunting the reactors with carborundum resistors. It is their opinion that the resistors damp out oscillation and thereby clear the system of disturbances which might build up very high voltages. One large operating company reports the successful operation of about 50 indoor 13,200-volt reactors equipped with resistors.

Losses in Reactors. During the past few years the cost of copper has been low and the cost of electrical energy high. As a result reactors can be economically designed with much lower losses than previously. One of the big advantages is on account of the reactor being able to withstand overloads and short circuits for greater periods of time.

The committee is working on a standard specification for reactors and hopes to have something definite to report before very long.

The committee expects to have three or four papers ready to present at one of the Institute meetings next year. Several of the papers will deal with the design features of reactors from the manufacturer's standpoint and at least one paper will give the experience of an operating company with different types of reactors over a period of eight years.

Subcommittee on Relays

E. A. Hester, *Chairman*

In accordance with the decision reached at the first Protective Devices Committee Meeting of this year, which was held on October 14, 1921, the Relay subcommittee has been actively engaged in the preparation of a paper utilizing the information collected from the replies to a questionnaire sent out by the previous sub-committee. In order to facilitate this work, an editing committee was appointed consisting of two operating and two manufacturing company representatives. On account of the fact that some of the information contained in this questionnaire was at least a year old it was found necessary to get into communication with most of the reporting companies and request up to date data on the various schemes which were reported. Information was also requested on any schemes which might have been installed since the original reply was made.

In addition to the data obtained from the questionnaire, there were also incorporated in the paper sections on the calculation of short-circuit currents, approved practises in relay application and notes on settings and tests. At the suggestion of some of the members of the Protective Devices Committee a section on methods of keeping records of operation were also included.

The question of cooperation with the Apparatus Committee of the National Electric Light Association in the preparation of a Relay Handbook has also been active. Mr. C. H. Sanderson of the New York Edison Company has been appointed Chairman of the N. E. L. A. Relay subcommittee and is to cooperate with the Chairman of the A. I. E. E. Relay subcommittee in this work. The Chairman of the Apparatus Committee and Protective Devices Committee with the Chairmen of the two subcommittees held a meeting in January and decided to prepare a tentative outline of the handbook as the first step in this work. Such an outline has been prepared and submitted to the various interested persons. On account of the work on the paper the A. I. E. E. Relay subcommittee has not had an opportunity of actively engaging in this work but now it is hoped that with the paper completed, the work may proceed more rapidly. It is intended to have the handbook completed some time this fall.

There are several questions which have been docketed for future study by the Relay subcommittee. These are as follows:

1. Protection of high voltage underground cable.
2. Further study of the use and merits of split conductor cable.
3. Apparatus protection. Former studies have been largely on transmission line relays. It is proposed to make a study of protection of generators, transformers, rotary converters, etc., and possibly to present a paper covering the investigation.
4. Special relay applications, such as those used in automatic and remote controlled stations.
5. Further study in standardization. A former subcommittee proposed a standard nomenclature for relays. This has been adopted by the Standards Committee, and there now seems to be a need for some standard form of symbols to represent various relays in single line schematic and detail diagrams. It is proposed to suggest a list of suitable symbols and if approval can be obtained, to use them in the N. E. L. A.—A. I. E. E. handbook.

H. R. Woodrow, *Chairman*

COMMITTEE ON ELECTROCHEMISTRY AND ELECTROMETALLURGY

To the Board of Directors:

This committee has not been active for some years, due principally to the facts that the subjects falling properly within its scope are more advantageously treated on the chemical and metallurgical sides than on the electrical, and have, therefore, been much more actively dealt with by some of the other engineering societies, notably the American Electrochemical Society and the American Institute of Mining and Metallurgical Engineers. At the outset this situation was discussed with the various members of the committee, of whom five showed an active interest in the work.

This discussion brought out in general that the usefulness of this committee lies principally in stating from time to time the status of the art, with particular reference to the power side, as even those members of the Institute who are furnishing electrical equipment to electrochemical industries do not seem very familiar with the essentials of the processes in which the power is used. It seems desirable at this time to make a general resumé of the various branches of the industry, giving a detailed statement of power requirements, and it is suggested that a symposium be arranged, a page or two being contributed by each of a number of men specializing in the various processes coming under this heading.

A second possibility for work on the part of this committee covers the subject of electrochemical corrosion to underground structures. This is a subject which has been neglected by the sister societies, due probably to the fact that it is a matter chiefly interesting public utility companies and in a sense parallel to inductive disturbances which fall exclusively within the province of the A. I. E. E.

It so happens, however, that there has been a special joint committee for a number of years working on this subject, a preliminary report of which has been recently published in bound form. It seemed to some of us that a public discussion of this report would be advantageous to all concerned, but this was opposed by the chairman of this special committee and at the present writing the President of the Institute has not come to any conclusion as to the desirability of action, although personally he appears to be in favor of it.

Discussion along the general lines of the conversion of chemical into electrical energy appears to belong, in the opinion of most of this committee, within the province of the Electrochemical Society. This, therefore, eliminates the discussion of the various forms of batteries as such, although leaving open their application, as, for instance, the use of storage batteries in power plants.

Altogether the most promising line of work for next year's committee would appear to be the preparation of the general symposium suggested earlier in this report.

LAWRENCE ADDICKS, *Chairman*

COMMITTEE ON TRANSMISSION AND DISTRIBUTION

To the Board of Directors:

The Committee on Transmission and Distribution submits its report for the year 1921-1922 under the following headings:

1. Report of the Cable Research Committee.
2. General Review of Construction Problems in Overhead Transmission and Distribution.
3. Underground Distribution Practise on Edison D-C. Systems.
4. Testing of Underground Transmission and Distribution Cables.
5. Foreign Practise in Transmission and Distribution Systems.
6. Review of Papers Submitted During the Year.

As in previous years and in line with the action taken by the Board of Directors a year ago, the report of your Committee summarized under the various headings records the historical progress made in the field covered by the committee, and secondly, indicates the direction in which future progress may be expected.

Your chairman desires to make particular reference to the report of the Cable Research Committee, which has been working jointly with the Underground Systems Committee of the National Electric Light Association.

In the matter of overhead transmission and distribution, as well as several of the other subjects in the report, the work was carried on by subcommittees appointed to investigate each particular topic and to confer with other engineering societies to obtain their views and as far as possible, to outline the tendencies in the entire field of transmission and distribution.

The section of the report dealing with foreign practise is the result of a questionnaire sent by Mr. C. T. Wilkinson, an English member of the Committee, to prominent engineers who are in close touch with European transmission and distribution problems.

REPORT OF THE CABLE RESEARCH COMMITTEE

During the past year, one American company has installed some three-conductor cable for operation with a normal working pressure of 33 kv. Other companies are seriously contemplating the installation of single conductor cable for three-phase transmission at 40 kv., 60 kv. and 66 kv. respectively. In the first case, the company is transmitting the energy from a generating station in one of the large cities to their surburban districts. In the other two cases the companies are receiving the current from overhead transmission lines, but on account of the objections to these high voltage lines in the thickly settled portions of moderate sized cities, they are proposing to use underground cable for transmitting the current directly to the distributing substations located in the center of the city. This plan will eliminate the extra step-down transformer substation at the city limits, which would otherwise be necessary. It is also reported that an English manufacturer has taken an order for ten miles of 55,000-volt three-conductor cable for use in Holland and also has completed and has on test a single length of 60,000-volt three-conductor cable.

In connection with these several propositions, it may be well to review our present knowledge and state of the art in this country with a view of determining to what extent the various elements in the design and construction of cables will limit the voltage.

1. Dielectric Losses. On this subject a number of papers has been presented to the Institute in recent years which have included examples showing the reduction in dielectric losses. The leading manufacturers in this country are now prepared to make dielectric loss guarantees on three-conductor cables up to 33 kv. normal working pressure, and on single-conductor cables for somewhat higher pressures. In the cables having high dielectric loss, the maximum permissible operating temperature is determined by the temperature at which the heating of the cable due to dielectric loss becomes cumulative. For low dielectric loss cables, the limiting temperature is that temperature which will cause permanent deterioration of the impregnated paper insulation.

It is now possible to get lead-covered cable with impregnated paper insulation and with a dielectric loss so low that this feature will not be the determining factor in limiting the voltage.

2. Maximum Permissible Operating Temperature of Impregnated Paper Insulation. The maximum permissible temperature for impregnated paper insulation in lead-covered cables is set forth in the Standards of the Institute as 85 deg. cent., while for similar material in electrical machinery, the limiting temperature is 105 deg. cent. This subject has been discussed in the committees of the Institute for a number of years, and a symposium of papers was presented at the Midwinter Convention in 1921. The views expressed at that time were so widely divergent that the Standards Committee decided that there was no hope of reconciling the conflicting views of the various engineers without additional data. The Research Subcommittee, has, therefore, arranged during the past year for a research investigation on this subject to be conducted by the Massachusetts Institute of Technology under the supervision of the committee. This work has been started and it is expected to continue over a period of about three years. The funds are being contributed by the N. E. L. A. and A. E. I. C.

For single-conductor cables intended for a normal working pressure of 66 kv. between conductors, the pressure to ground would be about 38 kv. and the maximum copper temperature according to the Institute Rules would be 85 deg. minus 38 deg. or 47 deg. cent. While this is about the same as the English practise for armored cables buried directly in the ground, it would be considered rather low in this country for cables to be installed in conduits, and particularly so if there were other loaded cables in the same conduit. Apparently it will be necessary to operate such cables at a very low current density or operate the cables at temperatures materially higher than those permitted by the Institute Rules. A number of the larger American companies however, are now operating their transmission cables as well as their low tension cables at temperatures appreciably above those permitted by the Institute Rules and without signs of depreciation of the insulation. It is suggested that this Institute Rule should be revised upward to correspond with the advances in the art.

3. Maximum Safe Dielectric Stresses. In the past we have apparently confused troubles due primarily to dielectric losses and dielectric stresses. A symposium of papers on this subject was presented at the June Convention. One of these papers indicates quite definitely cable failures due to dielectric stresses are quite rare. In Table I are given data on high voltage cables in this country and in several foreign countries, from which it will be noted that a number of foreign cables are operating at dielectric stresses materially higher than any that are used in this country. This tabulation has been made from data secured from a number of sources; the data regarding the English cables have largely been published in the English technical press and the statements indicated that the 33 kv. cables were being installed for ultimate operation at that pressure, but most of them were being operated at the start at a lower voltage. The best information obtainable however, is that at least one of these cables is now operating 33 kv. The statement is also definitely made that the 33 kv., three-conductor cable in Normandy has been in actual operation since 1914. The single-conductor cable at Barcelona, Spain, has also been in operation at 50 kv. normal working pressure since 1914 without any cable failures except one caused by electrolysis.

TABLE I

DATA ON HIGH-VOLTAGE CABLES

Location	Date	Normal operating voltage	Size of conductor cm.	Thickness of insulation		Maximum dielectric between conductors kv. per cm.	Stress to sheath
				Conductor	Belt		
				Inches	Inches		
1 Chicago	1921	33,000	350,000	0.297	0.11	29.4	26.7
2 St. Paul	1900	25,000	66,400	0.281	0.125	32.8	27.2
3 Manchester	1921	33,000	382,000	0.25	0.25	32.3	22.8
4 Birmingham	1921	33,000	255,000	0.25	0.25	34.6	24.4
5 English Cable	1921	33,000	95,500	0.25	0.15	41.5	33.6
6 Normandy	1914	33,000	79,000	0.216	0.216	47.8	33.4
7 Paris	1921	60,000	295,000*	0.538	..	..	40.5
8 Erith (England)	1921	33,000	320,000	0.25	0.25	33.6	23.4
9 Rome	1913	30,000	39,500	0.473	†	47.7	
10 Florence	1916	40,000	148,000*	1.18	..	22.3	
11 Turin	1916	38,000	138,000*	0.67	..	28.7	
12 Turin	1917	38,000	99,000*	0.646	..	31.4	
13 Rome	1919	30,000	49,400	0.630	†	38.7	
14 Naples	1919	32,000	237,000	0.590	†	30.6	
15 Rome	1920	30,000	59,000	0.552	†	39.8	
16 Barcelona	1914	50,000	99,000*	0.552	..	45.1	
17 Clyde Valley	..	33,000	237,000	0.512	†	34.4	

Sources of information:

1, 3, 5, 7 Private sources.

2 Transactions, A. I. E. E., Vol. XVII, 1900.

4 *London Electrical Review*, April 22, 1921, Page 528.

6 M. Delon at N. E. L. A. Convention 1921, discussion on Underground Systems Report.

8 *Electrical Times* (London), Sept. 29, 1921.

9 to 17 From Mr. Guido Semenza, Milan, Italy.

No. 1 has sector shaped conductors; all others are round.

Dielectric stresses calculated according to Davis & Simon (Journal A. I. E. E., January 1921).

*Single conductor cables. All others are 3 conductor.

†Not given.

In an Institute paper several years ago the statement was made that when the dielectric stress exceeded 20 kv. per centimeter, ionization would occur. Shortly afterward a paper appeared in the technical press giving a list of cables that had been in operation for a number of years in this country at materially higher stresses. One of them, the 25,000-volt cable on the St. Croix-St. Paul transmission line, is given in the above table.

Engineers are not in accord as to the maximum permissible dielectric stress nor which particular dielectric stress it is that is the limiting feature in high-tension cable design. Some engineers think that it is the maximum stress next to the conductor, but others think that it is the average stress, that is, the total voltage divided by the thickness of insulation. An English engineer contends that the limiting stress is determined by the stress next to the lead and published some data which appeared to support his theory. With such widely divergent opinions, we are apparently not prepared at this time to set the exact limit of dielectric stress that is permissible, but we can be guided however, by the stresses that are found on cables that have been in successful operation for a number of years. Our information along this line should be considerably extended if in the future we are to design high-voltage cables scientifically with the thickness of insulation properly proportioned to the working voltage.

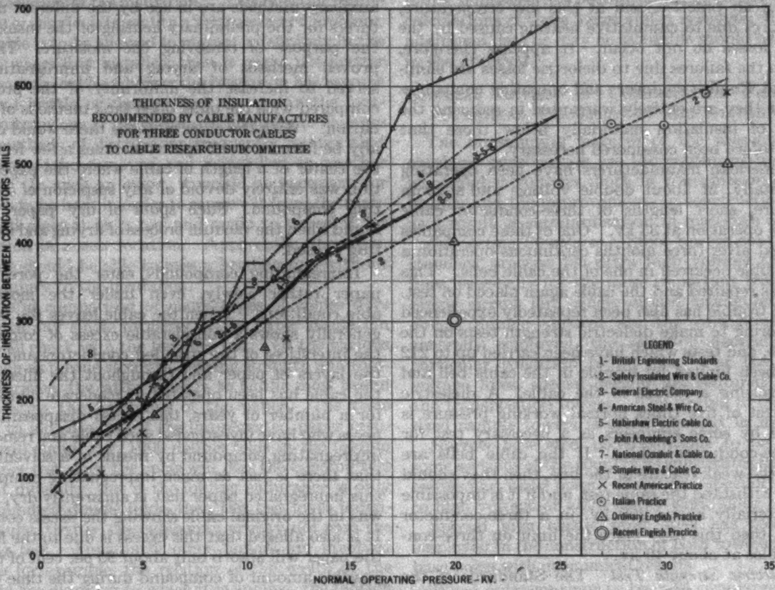

FIG. 1

4. Thickness of Insulation. The Standards of the Institute give recommended thicknesses of rubber insulation for various sizes of conductors and working voltages, but they do not include any such recommendations for impregnated paper or varnished cambric insulation. In 1920 the N. E. L. A. Underground Systems Committee included in its report a tabulation of thicknesses of insulation being used by the larger operating companies throughout this country. These thicknesses varied over a rather wide range, and accordingly the committee secured from the American manufacturers their recommendations for the thickness of impregnated paper insulation for various sizes of conductors and working voltages. These recommended thicknesses are shown in Figure 1. In the same figure are also shown the recommendations of the British Engineering Standards Association, several examples of ordinary English practise, the thicknesses being used by one of the larger American operating companies, and also the thickness being used by one of the leading English companies for 20,000-volt cable.

From this figure it will be noted that ordinary English practise is appreciably below the minimum recommended by any American manufacturer, and also that the recent thickness adopted by one English company for 20,000-volt cable is 25 per cent below their previous practise, and about 30 per cent below ordinary American practise. In Italy the high voltage cables apparently have about the same thicknesses of insulation as are used in this country.

English practise for the installation of underground cables calls for the cables to be made up with steel armor and jute covered and laid directly in the ground. Their conditions for the radiation of heat from the cable are therefore very much better than in the ordinary American practise of cables installed in conduits. According to the best information obtainable the English operating companies carry about the same loads on the various sizes of three-conductor cables as are customary in this country, but because of the improved facilities for radiating the heat, their maximum operating temperature of the copper is about 50 deg. cent. The dielectric losses in their cables are about the same as the best American practise, and at this low temperature, cable failures due to cumulative heating caused by the dielectric losses do not occur. It appears therefore, that when the failures due to dielectric losses are eliminated, that English engineers and operating companies think that they are entirely warranted in reducing the thickness of insulation materially below those that have heretofore been considered necessary.

Two American manufacturers have been operating experimentally, at about double voltage and at room temperature, short lengths of three-conductor cable made from operation at 33 kv. One of these companies reports that after three months continuous operation a case of trouble occurred in one of the cable bells. This trouble was repaired and the cable again placed on test. Cable bell trouble has also been repeatedly experienced in endeavoring to make dielectric strength tests on the same cable, and tests which have been carried up to 212 kv. have been limited by trouble in the cable bell and without causing a failure in the cable. A dielectric strength test of five times normal working pressure is considered by some engineers as a necessary test for their three-conductor cables. If the cable bells are not to be the weak feature of the line, then they should be able to withstand the same test, and if it is impossible to go materially above 200 kv. in a three-conductor cableb ell, then this may place the limit on three-conductor cables at about 40 kv.

5. *Dielectric Strength Test.* The Standards of the Institute mention dielectric strength tests on cables, but cover only the maximum length of the sample to be tested and the limiting temperatures. The rules also specify the test voltage to be applied to full reels of varnished cambric and impregnated paper cables at the factory, but there is nothing in the Rules to give the ratio between the dielectric strength test and the high voltage test applied to full reels. If it is the intention that the Standards of the Institute will prescribe tests which will determine whether or not the cable is satisfactory for the proposed working voltage, then it is submitted that the rules should include a dielectric strength test so as to insure that the cable has a proper factor of assurance.

6. *Impregnation of Paper Insulation.* Some years ago practically all American manufacturers used a vegetable oil base compound for impregnating the paper insulation, and generally these were rosin oil compounds. Cables with paper impregnated with these compounds were entirely satisfactory for the lower working voltages, but in their efforts to reduce the dielectric losses, the leading American manufacturers have gradually changed to a mineral oil base compound. About three years ago the percentage of vegetable compound, as shown by the saponification test, ranged from 0 to 35 per cent, while at the present time the maximum is about 10 per cent.

Practically all manufacturers now use the vacuum process of drying and impregnating, but a number of auxiliary methods are in use by the different manufacturers for the preliminary heating of the insulation for the purpose of removing the moisture. These improved methods of drying and impregnating have served to increase the uniformity of the product as compared with the older open tank methods of impregnation. With the older methods there would occasionally be found a small spot sometimes a few feet long in the center of a length of cable where the paper insulation was entirely devoid of any suspicion of impregnating compound. Such spots of dry paper are not found when the vacuum process of drying and impregnating is used.

Impregnating compounds enter the pores of the paper rather slowly, even under the most favorable conditions. When the cable leaves the factory it generally shows a considerable excess of compound in the interstices of the stranded conductors and between the layers of paper and throughout the fillers. After the cable has been operated at moderate temperatures for a number of years, this excess disappears. Engineers who have investigated such cable and removed the impregnating compound by means of a solvent, report that there is just as much impregnating compound in this impregnated paper that is apparently dry, as there was in the original cable showing the excess compound. It is also alleged that this excess is due to the fact that the paper will absorb only about 90 per cent of the total possible amount of compound during the time that the cable is in the impregnating tanks. It is suggested that with the tendency to higher operating voltages for underground cables it may be found desirable to have some excess compound inside the lead sheath so as to prevent ionization troubles.

One foreign manufacturer is using a thin transformer oil for the impregnating compound and finds that in this way he can get very low dielectric losses. Some American manufacturers have been aware that very low losses could be obtained in this manner but have not pushed the use of this compound as they did not consider that the cable would be entirely satisfactory in other respects. In addition, it is to be noted that the lowest losses reported with the use of this thin transformer oil are not materially below the minimum losses which have been reported by one American manufacturer with a mineral base compound. It, therefore, appears that the American manufacturers should continue their recent improvements in methods and materials for the impregnation of high voltage cables, and exhaust the possibilities for reducing the dielectric losses by these means before attempting the use of a very thin impregnating compound.

7. *Depreciation of Impregnated Paper Insulation.* In order to determine the maximum permissible temperature for impregnated paper insulation, when subjected to heat alone, and also when subjected to heat and dielectric stresses in combination, it is necessary to devise some laboratory tests which will serve to measure the depreciation of the insulation. This question, while apparently simple, is in reality a very awkward problem. If the cable is to be allowed to remain indefinitely in the position where first installed, then it might not matter for low voltage cables whether the insulation has become somewhat brittle or charred, but changes in the location of substations or the shifting of business, or changes in the methods of distribution frequently require that cables should be removed and reinstalled in another location. In such an event, it would be necessary for the cable to be bent in order to remove it from the manholes and place it on a reel and again to unreel it for installation in a new location. Apparently, therefore, the cable should be able to pass a bending test without serious injury to the insulation.

A careful comparison of many types of cables does not reveal any single property of the paper insulation which will check with the bending test. Of the various tests such as tensile strength, tearing strength and folding endurance, the latter appears to be the most useful as indicating the toughness of the paper. The tests appear to indicate that if the impregnated paper insulation will stand, say, 1000 double folds in the folding endurance test, then the cable will pass the bending test without difficulty, but if the folding endurance is only a few hundred double folds, then this test gives indefinite results, that is, the cable may or may not pass the bending test. Apparently other factors are involved such as for example, the relation of the width of the paper to the diameter to which it is applied, the tension on the paper, and the amount of lap. The latter variable can be eliminated by applying the strips of paper without lap, and several American manufacturers are now making their high voltage cables in this manner.

This subject of depreciation of the impregnated paper insulation is one of the problems now being investigated by the Massachusetts Institute of Technology as a preliminary step in the studies to determine the maximum permissible operating temperatures with and without dielectric stresses, and the committee would welcome discussion or suggestions from engineers who have had experience along these lines.

8. *Sheath Losses in Single-Conductor Cables.* When single-conductor lead covered cables are used for the transmission of heavy alternating currents, the lead sheath acts as a secondary of a current transformer, of which the primary is the main conductor. In order to prevent high voltages between the lead sheaths of the cables, it will be necessary to bond the lead sheaths at frequent intervals probably in every manhole. The resulting sheath currents may reduce the carrying capacity of the cables by 10 or 15 per cent, the amount of the reduction depending upon the spacing of the cables, the thickness of the insulation and the size of the conductor. The losses in the lead sheaths must also be taken into consideration in calculating the efficiency of the transmission as in amount they may be greater than the dielectric losses. The amount of data heretofore published has been insufficient to make accurate calculations of these losses and it is suggested that such additional data as may be available should be published in the JOURNAL.

GENERAL REVIEW OF CONSTRUCTION PROBLEMS IN OVERHEAD TRANSMISSION AND DISTRIBUTION

The outstanding features of the present status of overhead construction are the continued tendency toward higher voltages, both in transmission and distribution, and the improvements in construction methods as a result of standardization in materials and design.

Supporting Structures. Steel towers continue to be standard practise for extra high voltage transmission lines, especially for the more important trunk circuits. Single circuit flat, single circuit triangular and twin circuit double vertical are the configurations most generally employed, the selection depending on the particular condition to be met. For the very high voltage lines, special designs are required for anchor and transposition towers. The testing to failure of full sized sample towers is often justified in new designs.

Narrow base steel poles continue to be utilized in some sections of the country as substitutes for both steel towers and wood poles. They are especially applicable to high voltage or extra heavy work along city streets.

Special high elastic limit steel has recently been employed in the construction of both towers and narrow base poles with economical results.

Wood poles continue to be used very largely not only for distribution but also for the more moderate voltage transmission lines up to and including 66 kv., and there are in this country a number of excellent examples of wood pole transmission lines at considerably higher voltages. Single wood poles are generally employed for wood pole transmission lines where the voltage is 66 kv. or lower and the spans are under 500 feet; beyond these limits because of the greater clearances and strengths required, it is customary to employ two-pole *A* or *H*-frame construction.

The guying of narrow base steel poles and of wood poles, especially on higher voltage lines, is receiving increased attention, particularly guy insulation, involving as it does a combined mechanical and electrical hazard, has been subject of much careful consideration.

Changes in economic conditions have necessitated changes in wood pole specifications and this year the new tentative specifications of the National Electric Light Association will make their appearance. They differ essentially from the old specifications in providing a larger number of classes from which selections may be made.

With the increased cost of wood poles, butt treatment is receiving the consideration which it deserves. It is now clearly recognized that the open tank treatment is a measure fully warranted economically on the more durable timbers, such as cedar and chestnut; while on those woods which tend to decay above the ground line, a pressure treatment of the entire pole is advisable. Operating companies are realizing that there are no excessive complications involved in the open tank treatment and that the greater length of life fully justifies this treatment in comparison with the relatively inadequate brush treatment.

During the past several years various companies along the southern border have come to realize that much of the pole deterioration which has heretofore been loosely termed "rot", is in fact not a true fungus rot, but is caused by the depredations of insects, particularly termites or white ants. The protection of poles from termites and the saving of poles already attacked offers an interesting field of research in which valuable work may be done.

Insulators. In a general way it can be said that the manufacturers have made good their claims of the past several years that insulators of the latest manufacture are not subject to the rapid depreciation which was the cause of such concern a few years ago. Both in suspension and pin type insulators, perfected methods of design, manufacture and inspection have resulted in a more dependable and substantial product. Research is continuing unabated and we may expect in the not distant future to see even more useful and dependable designs, particularly in the line of high-strength, high-capacity units for extra high-voltage circuits.

The use of static shields to effect the double purpose of equalizing the stress distribution over long strings of suspension insulators and to obviate cascading in case of flashover, is becoming general on extra high-voltage lines.

Various new designs of pins for high-voltage pin type insulators are making their appearance on the market. In particular, the character of thimble is receiving close attention, it being well known that certain types utilized in the past have resulted in high insulator depreciation, and that failures have been incorrectly attributed to insulators which were in reality initiated by the pins.

A standardization of the rating of pin type insulators on a basis of leakage distance, flashover and other physical characteristics, eliminating the nominal voltage rating, appears highly desirable.

Increased attention is being given to insulator selection, as it has become evident to operating companies that in making a selection for any given line, close consideration must be given to climatic and economic conditions. The degree of over-insulation which is advisable or necessary, obviously depends on the relative importance of continuity of service on the particular line in question and the climatic conditions under which it will operate. In particular, the frequency of occurrence of lighting, temperature ranges, both daily and seasonal, humidity, the frequency of cleansing rains and the presence of wind-carried salt spray, dust or the fumes of industrial plants, must be given close consideration. It is only too evident that many of the insulator failures of the past have been due to incorrect selection, to an acceptance of a catalog rating which at best can be only nominal since it ignores the important variables mentioned above.

Engineers who have given the insulator much study believe that the insulator unit for 220 kv. should be larger, so that the number of units may be reduced to about the same number as now used for 100 kv. The following are desirable features for any new insulator design:

1. Length of unit increased to give larger arcover per unit, will use porcelain puncture value to better advantage; and give about 50 per cent more leakage length per given length or string, due to the elimination of one-half the metal connectors.
2. The reduction of the number of units gives much better natural potential distribution and simplifies shield problem.
3. The arrangement of porcelain to metal parts should be such as to reduce air and leakage stresses and eliminate corona.
4. Porcelain surfaces should be arranged to facilitate cleaning by storms and so arranged as to break up the continuity of water streams, which may result from rain, dew or fog.

Conductors. But little change is noted in the line conductor situation. Copper, copper-clad steel, aluminum, steel-cored aluminum and steel continue to be most largely used. For extremely high-voltage lines the nature of the conductor is often determined by limitations of corona.

Increased attention is being given to copper quality. Many companies have found, both for transmission and distribution purposes, that medium hard drawn copper has many of the advantages of hard drawn, without its corresponding disadvantages, and therefore are standardizing on this quality for all overhead purposes.

Close attention is being given to stringing and sagging, various methods using dynamometers or sighting targets, being employed. The attachment of conductors to either pin or suspension type insulators is being given careful consideration. Some form of shim is usually found advisable between conductors and suspension insulator hangers. Full flexibility of suspension strings in all directions at the tower support has been found desirable, conductor breakage having been noted where the lateral motion was restricted. Sleeves or other mechanical connectors, avoiding the use of solder, long standard on aluminum conductors, are found equally desirable where copper conductors of other than annealed grade are employed.

Miscellaneous Line Hardware. Standardization of line hardware and miscellaneous appliances continues to go forward under the auspices of the National Electric Light Association and much useful work is being done along this line.

Line Sectionalizing and Protective Devices. With increased voltages it is logical that line protective and sectionalizing devices, including fuses, switches and lightning arresters, should receive more careful consideration. Many new and useful devices are constantly appearing on the market, and operating companies now find available a wide selection for any voltage or character of service. Air and oil break switches have improved materially in the last several years. Fuses, particularly for the higher voltages, continue to be a source of difficulty, and some useful research work remains to be done thereon.

Construction Progress. The past year has seen the completion of the highest voltage transmission line to date, this being the 165-kv. line of the Great Western Power Company from Caribou to Valona, California, a distance of 199 miles. Likewise, the year has witnessed the first actual construction of lines to operate ultimately at 220 kv. The Pacific Gas & Electric Company of San Francisco has under construction a 220-kv. line from Pit River Power house No. 1, in Shasta County, to Vaca in the Bay region, a distance of 202 miles.

The Southern California Edison Company has begun the remodeling of its two Big Creek lines, from Big Creek to Eagle Rock, a distance of 241 miles, for 220 kv. operation. These lines are now operating at 150 kv., but the increased power to be transmitted renders the raising of the voltage imperative. It is interesting to note that the Southern California Edison Company has already had in operation, 27 miles of one of the Big Creek lines at 280 kv. and 240 kv. for experimental purposes. This experimental operation was unusually successful, and demonstrated that the addition of a static shield would make feasible, operation at the higher voltage without increased insulation.

Not only do transmission voltages continually show an upward trend, but likewise there is noted a tendency toward increasing the voltage of distribution lines. Increased loads and areas covered have finally made evident the inadequacy of the customary 2300-and 4000-volt circuits for many distribution problems, with the result that 6.6, 11, 13.2 kv. and higher voltages are now entirely standard in many districts for purely distribution purposes. This is a logical outgrowth, first, of the higher voltage agricultural lines, for many years thoroughly standardized in the far west; and second, of the urban substation to substation moderate voltage transmission lines, which it became frequently necessary to tap for larger power customers during the war period. The result has been that companies have become familiar with the economic advantages of true high voltage distribution lines, stepping down directly to the customer's service voltage without the interposition of subsidiary voltages. For such lines automatic induction regulators and other distribution devices are rapidly becoming standardized and in the not distant future we may expect urban and suburban distribution at voltages above 10 kv. to be an ordinary procedure.

The rural line problem continues to be largely an economic one. The types of construction which should be used are well known; the difficulty lies in justifying proper construction for the scattered business involved.

UNDERGROUND DISTRIBUTION PRACTISE ON EDISON D-C. SYSTEMS

Low-Tension Feeder Cable. With the relatively steady increase in density of Edison loads, it has been found desirable to increase the size of feeder conductors to as large a figure as may be installed safely, or as the existing ducts will admit.

In all but a few of the largest systems the cables contain no pressure wires. Pressures at the feeder junction boxes are frequently taken over special multiconductor pressure cables, or in some cases calculated drops are used to estimate what voltage may be delivered at the feeder terminals.

The use of self-contained pressure wires in the feeder cables is quite generally opposed, for the reason that experience has shown that these wires are a very general source of failure; but where the use of this type of cable has persisted it has been found possible to eliminate the possibility of failure due to poor cable design, which was the fundamental cause of dissatisfaction.

A very decided point in favor of the use of feeder cables containing pressure wires has resulted from the adoption of circuit breakers to be installed in the junction box at the feeder termination. These circuit breakers are connected through one of the pressure wires so that they may be tripped either by closing the switch in the substation or as the result of the pressure wire being energized when a fault occurs in the cable itself.

This arrangement gives instant notice of development of serious grounds throughout the length of the cable, and since its general adoption it has practically eliminated serious feeder cable burn-outs.

Edison Mains. The divergence in opinion and practise as to type and sizes of cables to be used for mains seems to be greater than in any other matter. Some companies use rubber insulated cables exclusively, whereas paper insulation is the standard of by far the larger number of companies.

The sizes of mains cable conductors generally range from 200,000 cm. to 2,000,000 cm. In many cases so-called "sub-feeders" of 1,000,000, 1,500,000 and 2,000,000 cm. are used to interconnect junction boxes without serving as supply for customers directly at all. In other cases the largest mains never exceed 500,000 cm., with the majority of the installation being of only 200,000 cm., and as these small mains are still giving adequate service on some of the largest systems, the question of whether the service given by the larger mains is commensurate with their cost, is very pertinent.

Junction Boxes. The practise as to when junction boxes are to be used is non-uniform to a large degree, and in this particular the tendency seems to be toward a still greater difference. Where Edison tube is used extensively it is agreed that junction boxes must be used frequently so as to provide suitable test points, but where cable in ducts is used the necessity for this is less apparent. Many companies have continued to use junction boxes with cable exactly as had been done with tube, while others have definitely abandoned the use of junction boxes except as feeder terminations,—and excepting always, existing tube. Practise and experience in this case have shown conclusively that there is no greater hazard evident without the junction box than with it for cable main systems.

Fusing Feeders and Mains. There is little or no change being made apparently in regard to whether mains and feeders are to be fused or not. Those companies which have always fused both mains and feeders, fear to change; those that have fused mains only, see no advantage in changing, but feel that they should not fuse the feeders in order to insure more continuous service, and those that have never fused either feeders or mains will not now install fuses, as it is their opinion that fuses would cause a definite lowering of their standard of service maintenance. Some of the engineers feel that it is better to have the fuses blow out than to burn the cable open, while the others feel that service should be maintained as long as possible regardless of overload conditions that may exist during an emergency. No definite agreement on this phase of operation seems to be possible because of the decided difference of opinion concerning the fundamentals involved.

TESTING OF UNDERGROUND TRANSMISSION AND DISTRIBUTION CABLE

As pointed out in the report of last year, this subject can be sub-divided as follows:

1. Testing at factory.
2. Independent laboratory testing by independent laboratories.
3. Acceptance inspection and tests.
4. Testing of installed cable.

1. Testing at Factory. Research work on the part of manufacturers is being carried on although there has been some temporary retrenchment in this direction by some of the manufacturers because of business conditions. On the other hand, certain manufacturers who had not done much research work heretofore are making relatively extensive preparations to do so. The general conditions in this respect are very satisfactory and much progress is promised for the near future,—a condition which could not have been said to be the case, so far as power cables are concerned, a few years ago. All of the progressive manufacturers are not only doing research work looking toward improvements in cable as a whole, but they are exercising more systematic control over the routine manufacturing processes and are giving more systematic attention to minor details, all of which is having its effect in improving cables in a very important respect, namely uniformity. However, no striking developments as a result of any of this research work have been announced during the year.

The practise in regard to the routine factory tests of finished cable has not changed during the year except that dielectric loss testing of occasional whole reels of cable at high temperature is now a regular factory test with several manufacturers.

2. Testing by Independent Laboratories. Research investigations by independent laboratories which have been completed or are now under way are referred to in connection with the report of the work of the Paper Insulated Cable Research Committee.

Independent laboratories are being more and more utilized for:

(a) Making the acceptance inspection and tests of cable being purchased under specifications.

(b) Making check tests of samples of new cable where the purchaser has not made any factory inspection or tests before acceptance and shipment.

(c) Investigating samples from cables which have given trouble in service. The standard tests made in such an investigation of paper insulated cable include composition and physical properties of the paper (tensile strength, folding strength and tearing strength), dielectric loss-temperature characteristic, composition of impregnating compound, ratio of compound and paper in insulation, thermal resistivity of insulation, effect of bending and dielectric strength.

3. Factory Acceptance Inspection and Tests. The specifications for paper insulated cable recently prepared by a joint subcommittee of this committee and the Underground Systems Committee of the N. E. L. A. are not only becoming more generally adopted, but, what is more important, more care is being taken by purchasers to see that the material supplied complies with the specifications. It has always been more or less customary for large purchasers to attach to their orders specifications which were more or less complete but more often than not, that was the only purpose which the specifications served. But there is undoubtedly a trend toward uniform specifications, a simplification which has obvious economic and other advantages.

There have bee nno innovations in the factory inspection and testing practise. The value of the bending test has been demonstrated on several occasions. The practise of measuring the resistance of the conductors of each length of cable,—(a practise which has not been universal heretofore) has been found to be well worth while as a check of deficiency in area, excessively short lay and errors in measurement of length. Most of the manufacturers have provided facilities for making dielectric loss tests on whole reels of cable so that now an occasional whole section can be tested as a routine matter.

The routine testing facilities of the manufacturers have, in general, kept pace with the advancement of the art, particularly, for example, in the case of dielectric loss tests, but there is one exception and that is facilities for making puncture tests of samples of cable. Operating voltages have risen to a point where samples of cables designed for such voltages, that is of the order of 33,000 volts and over, cannot always be tested with entirely satisfactory results due to either insufficient voltage being available or, what is more generally the cause, defective methods of preparing the ends and attaching the test leads. With still higher operating voltages being contemplated, this matter becomes more important and it is therefore obvious that the manufacturers have an immediate problem of developing a means of making thoroughly satisfactory tests of this character.

4. Tests of Installed Cable. The use of direct potential rather than alternating potential for high-voltage tests of installed cable is being investigated by operating companies. The large size of the testing equipment which is required for alternating potential tests because of the large charging current, makes it highly desirable to find a satisfactory d-c. method.

For several years one of the larger manufacturing companies has been making direct-current cable testing outfits using a thermionic valve (kenotron) for rectifying purposes. This device is particularly valuable in connection with long high voltage transmission cables. For example, in order to test a 33-kv. transmission cable fourteen miles long at double voltage after installation, as required by the Institute Standards, a transformer of about 2500 kv-a. is required. If a d-c. outfit is used for the purpose, the capacity can be reduced to about 5 or 10 kw. if the outfit is used only for making the high voltage test. However, for reducing the fault after failure so that the trouble can be located, it is necessary to be able to burn the insulation with the high voltage testing set so that the resistance of the fault will be within the reach of the lower voltage testing facilities available, and this may make it necessary to increase the capacity of the d-c. testing outfit to about 50 kw. Even in this latter case, however, the cost is only about one-quarter of the cost of the a-c. testing set.

One of the larger companies has installed one of these direct-current testing sets for use in testing high-voltage lines. While the experience to date does not warrant any definite conclusions it appears reasonable to hope that, with the co-operation of the manufacturers, so as to adapt the device to operating conditions, and with more experience in the use of this testing outfit, it will be possible to entirely eliminate the difficulties that have been encountered and thus render this scheme of testing available for high voltage transmission cables.

In this connection it should be pointed out that all of our experience heretofore has been with the use of alternating direct current for testing purpose and that before the use of direct current for this purpose can be considered successful the proper ratio between d-c. volts and a-c. volts, to secure the same results, should be definitely known. Foreign investigations indicate that this ratio should be about 2.5, but the American manufacturers up to the present writing have not been willing to agree to a ratio higher than 1.5. If the ratio of 2.5 is correct, then a test made with the direct-current voltage limited by a ratio of 1.5 will be entirely without value, as it is not high enough above the normal operating voltage to give results that are at all comparable with those heretofore obtained with alternating current. Two of the cable manufacturing companies have undertaken to make tests of this character and results should be available very shortly. In view of the importance of this ratio, it is recommended that the Standards Committee investigate this subject and incorporate the proper ratio in the Standards of the Institute.

FOREIGN PRACTISE IN TRANSMISSION AND DISTRIBUTION SYSTEMS

The data on this subject have been submitted by foreign engineers of such prominence that it may be taken as representative of the best and most reliable opinions in their respective countries, namely, England, France, Italy and Norway.

The maximum voltage for transmission systems now in operation in any of the four countries is 110,000 volts. This system which is in Norway is 55 miles in length and has an ultimate capacity of 75,000 kw. In Italy the Pescara system operates at a maximum voltage of 88,000 volts and the maximum length of transmission in bulk is approximately 115 miles. The Energie Electrique du Littoral Mediterranean system is the most important high voltage system in France, and is composed of 560 miles of overhead lines operating at voltages varying from 55,000 to 30,000 volts, and 870 miles of overhead lines operating at voltages varying from 13,000 to 10,000. The total capacity of this system is 111,900 kw. The Societe Hydroelectrique de Lyon system operates at 70,000 volts but is a much smaller system, being composed of 105 miles of overhead lines and having a capacity of only 2984 kw. There is now under construction in France a transmission system to operate at 125,000 volts. The most important English overhead system is that of the North-East Coast Company, the connecting lines of which run from Newcastle up through Northumberland to the southern border of Scotland, and south from

Newcastle through Durham into Yorkshire. This system operates a considerable mileage of overhead transmission line with the great majority of it on wooden poles. The voltage of this system is 30,000 volts. A short transmission line operating at 33,000 volts has recently been put into operation for supplying the City of Chester.

The maximum voltage reported for underground cables in actual operation is 40,000 volts. This is in Italy where underground cable is operated at 40,000 volts on one system, at 30,000 volts on five systems, and at 25,000 volts on six systems. The distribution system for the City of Christiania is composed of 30 miles of underground cable operating at 35,000 volts. In England a 33,000-volt cable has been in operation some time in the Manchester district and a 66,000-volt cable under the River Tee is ready to be put in operation. In France, the Union d' Electricite, a consolidation of a number of small systems around Paris, is at the present time installing a 60,000-volt underground cable system with single-phase cable.

With regard to the comparative reliability of overhead and underground systems, from the point of view of continuity of supply, the opinion in all four countries is that underground cable gives the least trouble. The State Railways of Italy use extensively cables operating at 25,000 to 27,000 volts as primaries for electrification and interruptions due to cable trouble are quite exceptional.

As to the comparative cost of overhead versus underground transmission for approximately the same reliability and continuity of supply, no definite opinions are expressed. In England, up to the present time there has been no great difference between the cost of an overhead line and that of a cable. The reason for this is that the allowances for wind pressure, ice and factors of safety were formerly so stringent that the expense of an overhead line was vastly greater than in the United States. The Electricity Committee of England has, however, brought these regulations up to date and they will soon be issued in pamphlet form. Several lines, based on the new regulations, are at the moment being projected and the estimates show that such lines will be closely comparable in cost with similar lines in America.

In France it is possible to install an overhead transmission line for less cost than a cable. Due to this and also the voltage limiting features of cable, it is the practise of the French engineers to consider only overhead transmission where possible. For Norway and Italy no opinion was expressed as it is thought the question depends very largely on local conditions.

The reports of the most serious troubles encountered in transmission systems differed in each country. In France the chief trouble is that of voltage regulation due mainly to the lines having been overloaded during the war and not having sufficient copper. With this exception the French engineers have experienced no special trouble. In Italy the only element of the line which causes trouble is the insulator and these troubles are not severe. Trouble has been experienced from the breakage of insulators after a number of years of operation. The fracture shows that the break is due to the expansion of the cement, and that the quality of porcelain is not altered by age. Lines in operation from 15 to 25 years are still in good working condition. English engineers have experienced no serious trouble in connection with insulators, towers or poles as the lines in England operate with such a large margin of insulation. Practically no troubles are experienced due to the expansion of cement or to insulator aging. On the other hand, a great deal of trouble has been experienced with insulators by the Norwegian engineers, due to cracking caused by the expansion of cement.

The tendency in all four countries is towards the use of higher voltages. In France the main sources of hydraulic power are over 250 miles from the Paris district, the center of power consumption, and the transferring of this power in large amounts is a problem which must soon be considered. This will necessitate the use of voltages from 165,000 to 200,000 volts. The Norwegian government is now contemplating the use of 150,000 volts on the lines from a new plant now being constructed. The Norwegian engineers are also considering the transmitting of power to Denmark at 220,000 volts three-phase or 200,000 volts d-c. In Italy several overhead 110,000 volt lines are under construction and in England 110,000-volt lines are contemplated.

In England, France and Italy the three-phase system of transmission is the only one considered. Only one direct-current system has been installed in the last ten years. Some Norwegian engineers are of the opinion that while three-phase transmission will take care of any overhead situation likely to be encountered, they are not at all certain that constant current would not be better in many cases on very long lines. They believe that direct-current transmission up to 200,000 volts and 250 amperes is entirely practical and that the insulator question will be greatly simplified.

The tying together of existing hydroelectric or steam plants has been carried out to a large extent in Norway and Italy. Practically all of the large plants in Northern Italy are connected together and similar ties with Middle and Southern Italy are contemplated. In Norway a number of 50,000 to 60,000-volt hydroelectric plants have been connected in the last few years. In France and England a great many of these projects have been contemplated, but few have materialized.

In regard to the arrangement of transformer connections for a system, the opinion of engineers in all four countries is in favor of having the high side connected Y and the low tension side connected Δ.

It has been the experience of the foreign engineers that protection against lightning and power surges on lines up to 60,000 volts is very difficult. In Norway the experience has been that the operation is equally good without lightning arresters as with them. In both Italy and Norway engineers favor the use of choke coils with resistance and also the use of ground wires. In England the majority of engineers favor the aluminum cell type of arrester. In France the operating companies object to the aluminum cell on account of its high cost and the necessary maintenance. The other types of lightning arresters in use in France do not give satisfaction on large systems.

As regards the use of outdoor substations the engineers of the different countries are divided in their opinions. The English and French engineers favor the use of the outdoor substation and the few in service in these countries have proved satisfactory. In Italy the opinion of the engineers is divided and in Norway no advantage is seen in an outdoor substation for voltages up to 60,000 volts.

The engineers of England, France and Italy have had very little experience with grounding coils, reactance coils or Dressel-Spuhle for limiting electric surges and no opinion was expressed. The Norwegian engineers have had some experience with the Peterson grounding coil and advocate its use on lines up to 66,000 volts.

REVIEW OF PAPERS SUBMITTED DURING THE YEAR

In the March, 1921, issue of the JOURNAL, Messrs. H. W. Fisher and R. W. Atkinson presented an article on "The Effect of Heat on Paper Insulation."

After discussing in detail the mechanical properties of paper especially as influenced by drying, heating, and impregnating, tests for measuring the changes due to these causes are considered. It is shown that the measurement for tearing resistance is a satisfactory test and two machines for this purpose are described. The results of tests made to determine the effect of heat upon the properties of paper are discussed and measurements of rate of deterioration of paper at different temperatures are given. The relation of these data to allowable operating temperature is considered, and emphasis is placed on the importance of not exceeding intended temperatures through lack of knowledge of conditions.

In the same issue of the JOURNAL is a paper by Mr. D. W. Roper on "Permissible Operating Temperatures of Impregnated Paper Insulation in Which the Dielectric Stress is Low."

This paper deals with the writer's experience with concentric cables which have been operated at high copper temperatures in Chicago. The author cites instances where the insulation of cables known to have been operated at a copper temperature of over 100 deg. cent. steadily throughout the day for a number of months, was found to be in good condition when the cables were removed for reinstallation elsewhere. In one or two cases he has found the copper temperature as calculated by Atkinson's method to be as high as 200 deg. cent. The author believes it desirable to establish two limits of copper temperature; the first to be a lower limit at which the insulation will not be injured even when the temperature is maintained for long periods of time; the second to be an upper limit above which it is known that the insulation will be injured if such temperature is maintained for any considerable time.

A paper on "Transformers for Interconnecting High-Voltage Transmission Lines" is presented by Messrs. J. T. Peters and M. E. Skinner in the JOURNAL for June 1921.

This paper brings out the advantages to be realized by the use of the star-star connection in interconnecting high-voltage transmission lines. This connection however, requires the use of an auxiliary winding in delta to stabilize the neutral point or to decrease the inductance in the ground connection. Consequently the great majority of transformers designed for interconnecting transmission lines are three-winding transformers. Another type of transformer which would be included in this general class is one having an auxiliary winding for feeding a synchronous condenser used in controlling the voltage at the receiver end of the line. The important features peculiar to three-winding transformers when used for interconnecting transmission lines are discussed and the way in which the design and performance of the transformers are influenced by these peculiarities is pointed out.

In the June 1921 issue of the JOURNAL there was an article by Mr. L. L. Elden entitled "Notes on Operation of Large Interconnected Systems."

After describing the interconnections made between the Boston Edison Company's system and the systems of the Eastern Massachusetts Electric Company and the New England Power Company, the author discusses the operation of these connections and the troubles encountered. Some trouble has been experienced on account of short circuits on the systems and to variation in frequencies, but as a whole the operation is considered satisfactory.

Messrs. W. I. Middleton and E. W. Davis presented a paper in the September, 1921, issue of the JOURNAL on "Skin Effect in Large Stranded Conductors at Lower Frequencies."

This paper deals with tests made by the writers to obtain experimental data concerning the effective resistance of large-size stranded conductors to alternating currents of the low frequencies of 25 and 60 cycles. The tests are described and the results tabulated and discussed. The results are also compared with those obtained by using three common formulas for skin effect, in order to determine how far and with what modifications one of the formulas can be applied to stranded conductors. Two of the conclusions drawn are that the skin effect of rope-stranded cables can be calculated to a fair degree of accuracy by assuming the same current penetration as for solid or stranded conductors, and that the current penetration should be calculated from the pitch diameter of the outside layer of strands.

"Use of the Tangent Chart for Solving Transmission Line Problems" is the title of paper presented in the

November, 1921, issue of the JOURNAL by Mr. Raymond S. Brown.

In this paper there is presented a method, devised by the author and based on hyperbolic functions, for solving transmission line electrical problems by means of a special diagram, called a tangent chart. After discussing the general conditions met with in transmission line problems and pointing out the advantages of the tangent chart, the author explains in detail the underlying theory. Diagrams and descriptions are given and the manner of using the chart is explained.

A paper on "Questions of the Economic Value of Overhead Grounded Wires" by Mr. E. E. F. Creighton is included in the January, 1922, issue of the JOURNAL.

After a general discussion of the history of overhead grounded wires and the mechanical vs. electrical factors, the author presents a detailed discussion on the functions of overhead grounded wires, relation of overhead grounded wires to cloud lightning, detrimental effect of grounded wires on semi-insulated structures, relation of grounded wire to direct stroke, overhead grounded wires on wooden pole structures, steel structures and overhead grounded wires. The author analyzes the functions of overhead grounded wires under nine distinct headings. The conclusion reached is that the overhead wire is, in general, a detriment rather than an asset to a semi-insulated or high-resistance pole-line structure. On metal structures no technical function is found detrimental. The relation between the earth resistance and the decrease in protection to insulators is yet to be determined.

The February, 1922, issue of the JOURNAL presents an article on "The Effects of Moisture on the Thermal Conductivity of Soils" by Mr. G. B. Shanklin.

The article describes some thermal conductivity tests made on soils containing different percentages of moisture and compares the results with those of other investigators. These results show that moisture is the predominating factor in determining the thermal conductivity of soils. The relative thermal capacity of various types of perfectly dry soils, such as sand, clay, gravel, etc., covers a range from only one or two, while the addition of moisture increases the range to five times or more that of dry soils.

In the February, 1922, issue of the JOURNAL Mr. E. E. F. Creighton presented a paper "On Deviations From Standard Practise in Lightning Arresters."

This paper is an endeavor to answer questions of practise and the criticism of arresters brought out in an investigation conducted by the Protective Devices Committee. The writer presents a brief review of some of the factors relating to arresters not of the electric valve type and points out the inefficiencies and objectionable characteristics of arresters of low discharge rate. The other extreme, namely, the practise of using no lightning arresters, is then discussed from three viewpoints and the conclusion is drawn that in all three cases the argument in favor of using no lightning arrester is dangerously faulty. A new method of inspection of aluminum arresters is proposed and experiments are given to show that the power factor of cells is a sensitive indication of their condition. The investigation of two arresters in service thirteen years without overhauling is described and the possibility of overhauling arresters in the field is discussed.

A paper on "The Petersen Earth Coil" by Messrs. R. N. Conwell and R. D. Evans was included in the February, 1922, issue of the JOURNAL.

The theory of the earth coils is explained and a discussion is given on the operation of the earth coil under various electrical conditions encountered on transmission systems. Attention is called to the fact that the installation of the earth coil necessitates a change in lightning arrester settings, is unsatisfactory on a transmission network protected by a relay system, and compared to a grounded neutral system will increase the voltage stresses which would be imposed upon line insulators, cable insulation, and switching equipment. Tests were made on a 26,400-volt, three-phase, 60-cycle network of five lines totaling 59.8 miles to obtain information relative to the operation of the Peterson earth coil and to collect data indicating the suitability of such an installation for the suppression of arcing grounds. These tests are described and the results are discussed. The authors have considered five methods of grounding the neutral and give an order of preference for each, from the viewpoint of voltage stresses, current stresses, relay operation, continuity of service and cost. In conclusion the advantages and disadvantages are discussed.

Mr. Herbert Bristol Dwight presented a paper in the March, 1922, issue of the JOURNAL on "Skin Effect and Proximity Effect in Tubular Conductors."

The purpose of this paper is to present sets of curves to determine the effective a-c. resistance of tubular conductors as required to be predetermined by designers for radio installation, for large underground cables with non-magnetic cores, and for electric furnace circuits. The basis of the curves and formulas given in this paper is explained and discussed. Curves are given showing the skin effect for isolated tubes and for stranded conductors. A curve is also shown for proximity effect ratio to be used when the return conductor is near. Typical examples are solved and in conclusion the writer expresses the opinion that it seems scarcely worth while to provide a non-magnetic core with a 2,000,000 cir. mil 25-cycle cable in order to reduce the skin effect, but in other cases considered, the tubular form seems very advantageous.

In the June, 1921, issue of the JOURNAL Mr. F. W. Peek, Jr. presented a paper on "Voltage and Current Harmonics Caused by Corona."

This paper deals with investigation made to study the effects of corona in producing voltage and current harmonics in transmission systems. Tests were made on short three-phase lines of very fine wire so that the corona loss would be excessive and exaggerate conditions. The different tests are described and the results discussed. Two of the conclusions drawn are that corona will cause voltage and current harmonics, of which the third is the most prominent, and that in properly designed practical transmission lines, the harmonic introduced by corona should be inappreciable.

In the same issue of the JOURNAL was a paper by Mr. Raymond Bailey on "Voltage and Power Factor Control of 66,000-volt Transmission Lines Connecting Two Generating Stations."

The problem which confronted the Philadelphia Electric Company, that of providing for the control of voltage and power factor of the two 66,000-volt transmission lines connecting its Schuylkill and Chester generating stations, is presented in this paper. An outline of the specific problem with its requirements, a discussion of the factors determining the selection of equipment, and a presentation and discussion of data on operating characteristics are included. The situation required that the control of voltage and power of the transmission lines permit of the transfer of energy of either direction, at suitable power factor, up to the rated kv-a. capacity of the lines, with the generating stations operating at approximately equal bus voltages. Other complications are also considered. The comparisons made to determine the most satisfactory type of regulating equipment and the reason for the selection of three-phase induction regulators are given and certain conclusions of more or less fundamental character are brought out.

Messrs. Edwin H. Fritz and George I. Gilchrest present an article on "Modern Production of Suspension Insulators" in the June, 1921, issue of the JOURNAL.

This paper records the progress made during the past few years in the production of electrical porcelain. The information covers the engineering and works organization, the manufacture, and design and test. Each of these topics is discussed in detail and explained. In conclusion the writers state that rapid strides in the manufacture of electrical porcelain have been made in the past few years and perhaps the greatest advancement is in the methods of production in the factory.

In the June, 1921, issue of the JOURNAL there appears a paper by Messrs. E. E. F. Creighton and F. L. Hunt, on "A Solution of the Porcelain Insulator Problem."

After a discussion of the main causes of insulator failures, the writers describe the satisfactory results of a method developed by them for eliminating the cracking of insulators due to the Portland cement. This method consists of thoroughly impregnating the cement, after it has set and thoroughly dried, with a pitch compound. Eleven hundred insulators made in this manner have been in service nearly three years without a failure. In conclusion the authors present comments on the mechanical strength, electrical tests treatment, line testing, aging of porcelain, and open porosity of porcelain.

Mr. W. W. Lewis presented an article in the June, 1921, issue of the JOURNAL entitled "Some Transmission Line Losses."

This paper deals with tests for corona loss made on a 30-cycle, 140,000-volt system and gives a full description of lines on which the tests were made. The tests are described and the results in the form of tabulations and curves are shown. These results are discussed in detail. The conclusions drawn from these tests are presented and it is pointed out that the tests indicate the desirability of operating a transmission line below the corona voltage, thus avoiding corona loss and its accompanying effects.

A paper entitled "Long-Distance Transmission of Electric Energy" by Mr. L. E. Imlay is included in the June, 1921, issue of the JOURNAL.

This paper discusses the long-distance transmission of electric energy from the economic viewpoint, the physical viewpoint and the point of view of service. The economic conditions which justify long distance transmission are pointed out and considered.

In dealing with the plant required for long-distance transmission some of the considerations that effect the design are discussed. A graphic method of determining line performance is illustrated by an example and essential data on other lines are given. Right-of-way, spacing of towers, line insulators, high-tension switches and lightning arresters are discussed.

Service is considered from the viewpoints of what people demand, what perfect service will cost, and the service that may be expected from a large interconnected system consisting of steam plants at the mines, hydro plants, wherever available, and local steam plants.

In the August, 1921, issue of the JOURNAL there is a short article on "Self-Corrosion Not Stray Current Electrolysis, Shown at Selkirk, Manitoba."

This paper describes the investigation of a case of chemical corrosion of iron pipe at Selkirk, Manitoba. The corrosion of the pipe was found to be due to the chemical activity of the solution of so-called alkaline salts in the soil.

Mr. F. G. Baum presented an article on "Voltage Regulation and Insulation for Large Power, Long Distance Transmission System" in the August, 1921, issue of the JOURNAL.

In this paper a standard frequency of 60 cycles is advocated for the national system, and 220,000 volts is proposed as standard for extra large-power, long distance transmission. The voltage regulation of transmission lines is discussed and a simple diagram is given which shows that for a 60-cycle, 220,000-volt line, the line charging current supplies about two thirds of the capacity current required for about 0.8 load or 320 ampere load current, and that for larger loads the synchronous condensers supply leading, and for smaller loads, lagging current. A system of regulation is proposed which will result in practically constant voltage at all points of the line at all loads. The advantages of such a system are given and discussed.

The problems of line insulation are discussed and especial attention is called to the necessity for low air and leakage resistance stresses and results of a large number of tests are given. A new diagram resulting from the analysis of experimental data is given. From this diagram the characteristics of long strings of insulator strings may be calculated, knowing the constants of the unit relatively. Illustrations are presented showing that wet and dry arc-over may be controlled but it is believed best to strive for the elimination of arcs. In conclusion the writer states that while present insulators with some form of shielding or grading will no doubt give more satisfactory results for a 220,000-volt system, such as he advocates, than is now obtained on lower voltage lines, it is desirable that further work be done with a view to developing the best way of handling line insulation.

In the February 1921 issue of the JOURNAL, Mr. Philip Torchio presented a paper on "Permissible Operating Temperatures of Impregnated Paper Insulation in which Dielectric Stress is Low."

After a review of the effect of temperature on insulating materials, abstracting from the 1913 Steinmetz and Lamme Report, and the 1905 British Engineering Standards Committee tests, the author questions the present temperature limit adopted for impregnated paper when used for low-tension cables. Results obtained from surveys of low-tension cables in large distributing systems, and also the results of special tests on cables including sheath cracking, high temperature tests, effect of bending on cables heated at high temperatures and distillation of cable compounds are shown and discussed. The vital importance of ambient temperatures in subway ducts as affected by the thermal conductivity of concrete, amount of moisture in the soil, different arrangements of ducts, and load factors at which the cables are operated, is pointed out. The conclusions derived by the author are that the permissible operating temperatures are to be a function of the load factors at which the cables operate, and he recommends 105 deg. cent., 95 deg. cent., and 90 deg. cent., for load factors of 33 per cent, 50 per cent, and over 66 per cent respectively.

In the same issue of the JOURNAL Mr. L. L. Elden has also contributed a paper on "Permissible Operating Temperatures of Impregnated Paper Insulation in which the Dielectric Stress is Low."

The conditions considered in adopting 85 deg. cent. as the limiting conductor temperature for impregnated paper-insulated, low-tension cables are discussed and conditions which hazard the safety of the cable when operated at the higher temperature limits are pointed out. The results obtained by a large operating company, one whose cables the limiting temperature of 85 deg. cent. has not been exceeded, are described and discussed. The practicability of operating cables on a load factor basis, or by specifying an allowable overload rating in terms of temperature is questioned. The conclusion drawn is that a conservative standard, such as the present Standard rule, is the more desirable policy.

A paper entitled "The Maximum Safe Operating Temperature of Low-Voltage Paper-Insulated Cables was also presented in the same issue of the JOURNAL by Mr. W. A. Del Mar.

The mechanical strength of low-voltage cables is discussed and a tearing test for paper is described. The results of experiments made to determine the effect of continuous heating are given and indicate that the mechanical strength of paper insulated cables is destroyed by continuous exposure to a temperature of 100 deg. cent. for three or four weeks. The author believes the operation of cables at higher temperatures than that allowed by the present Standards is in the nature of a gamble and questions whether the Standards should take cognizance of it.

Mr. Wallace S. Clark contributed a paper entitled "Notes on the Effect of Heat on Impregnated Paper from Cable Insulation."

This paper covers tests made to determine at what temperature marked deterioration in the paper of impregnated paper cable took place. The tests are described and the results given and discussed. The conclusion drawn is that the temperature limit fixed for the operation of a low-tension cable, to avoid undue deterioration, must take into consideration the length of time during which temperature is maintained.

E. B. MEYER, *Chairman.*

TRACTION AND TRANSPORTATION COMMITTEE REPORT

To the Board of Directors:

In conformity with the President's request for a discussion of some phases of the conditions prevailing in the field covered by this Committee, we beg leave to submit the following:

The year has been practically devoid of large or interesting developments in the electric transportation systems in the United States. The use of the one man car, trackless trolley and the motor bus has become more general in the light traction field but in heavy equipment construction activity has been limited almost wholly to foreign countries.

The introduction of important new or novel ideas in traction equipment also has been largely lacking and those engaged in engineering in this field appear to have been occupied mainly in efforts to standardize and perfect equipment of existing types and to adapt them to special local conditions.

In the face of such a situation, we have found a dearth of technical material for subjects of papers and discussions that did not promise to degenerate into a rehash of old and threadbare questions. Exhaustive treatments of electrification of steam railroads such as that presented in the recent Super Power Report have covered very completely most of the technical aspects of this problem. The question then naturally arises whether the limitation of the Institute's papers and discussions to more or less technical electrical detail subjects is either wise or a full performance of our duty as a trained body of men with special information at our command which might be beneficial to the public if presented in a form readily grasped. Is there not a further obligation upon us?

Is there not an equal duty laid upon us to give to others not technically equipped a clearer view and better understanding of great public questions which to be wisely solved must be based on a sound engineering foundation? Is it right to confine our papers and discussions to the engineering detail technique of great subjects for the sole benefit of our own and our professional brethren? By such a procedure do we not stand aloof from the great national and world problems creating the impression that we do not comprehend their wider phases or are timid about venturing beyond our own limited self-prescribed professional boundaries?

Take for instance the steam railroad situation as it is before the country today and the bearing of electrification thereon. We have had ream upon ream of papers and hours without end of discussion of direct vs. alternating traction and coal economy of, steam vs. electric engines.

How often have we gone below the surface and discussed the function of railroads as a necessity in the life of our country (the United States) and the fact pointed out by such far-seeing men as President Willard that in the immediate future it is not a question of rates but a question of capacity which we face when business shall again become normal?

There is no longer need for technical discussions of whether electric traction will add capacity to a given railroad track system; that is admitted, demonstrated, and settled. Practically every steam railway in the country has an electrification problem of some sort under consideration and on the larger systems there are many such.

To carry them out and to make possible any general advance toward a wider use of electric traction on our great national arteries, public opinion must first be awakened to the basic economic facts and a general nation wide realization must be created of the necessities of these systems. A clear conception of the fundamental function of these railway lines to the nation as well as the effect upon general business of their failure to keep in step with the growth of the country is not easily acquired and yet it must come before we can secure full financial support for the program which must come before long. The Chairman of the Joint Committee of Congress recently stated as follows:

> "We believe that the transportation facilities of the country must be placed upon a solid foundation. It will not do to make up deficits by appropriations of public funds. The railroad companies must be operated with the expectation that the gross revenues will be sufficient to cover operating expenses and leave a reasonable return upon the investment. It is of paramount importance to the public welfare that the transportation companies be made going concerns; that they be placed upon a substantial foundation in every respect, and that the operating expenses be reduced by careful and efficient management."

Is not this news to many people and is the situation not one warranting our best analysis?

The engineer has a trained mind familiar with the physical facts of this subject, he has acquired the habit of straight honest thinking step by step from premises to conclusion, why should he not broaden out his field and embrace the opportunity to inform and build up public opinion upon sound facts and impartial criticism.

There are many engineers who are members of this Institute who seldom or never appear or take part in discussions because their field has broadened and they no longer deal with details. Why should we not bring in these men and popularize, if you please, for the benefit of the public this subject so that by our keen logic of presentation of the economic facts we may attract the attention and interest of the mind of the man on the street.

Here is a really big subject of vital importance to the life and prosperity of the nation. We have the training and the knowledge, why should we not step outside the narrow confines of our technical field and show that engineering is more than handling kilowatts and kilovolts, that it is and must ultimately be the controlling factor in the economics of many natural problems if they are to be solved permanently.

H. W. BRINKERHOFF, *Chairman*

TELEGRAPHY AND TELEPHONY COMMITTEE

To the Board of Directors:

During the past two years the Institute has to an increasing extent served as a clearing house for information dealing with technical advances in telegraph, telephone and radio engineering, one direct result of which is the rapidly growing number of communication engineers applying for membership in the Institute.

Electric communication engineering in all its branches made marked progress during the war years and the improvements made to meet the needs of war have as rapidly as economy permitted been applied to the needs of peace time and of commerce.

One of the features of the committee's plans which has been followed closely is that of providing for the presentation of technical papers at meetings of the Institute giving detailed information of the noteworthy advances made in the various departments of the art. It may safely be stated that the present progress of communication in all its branches is recorded in the various papers published in the Institute JOURNAL during the past two or three years.

PROTECTIVE DEVICES

It has been suggested that the Protective Devices Committee of the Institute might to advantage include in its investigations a study of the problems of communication line and apparatus protection against lightning disturbances and accidental contact between power wires and communication wires. The subject has been given engineering consideration by individual companies but a wide diversity of devices is used on lines throughout the country and it would seem that there is opportunity for standardization of devices to meet like conditions in various localities, both in railroad and commercial line operation, telegraph and telephone.

INDUCTIVE INTERFERENCE PREVENTION

The movement mentioned in last years report of increasing cooperation in studying the needed procedure in the coordination of signal and power circuits has gone forward with growing impetus during the present year. This effort is general among all of the utility interests concerned and reflects a recognition on all sides of the mutual nature of the problem and of the duty of all to so harmonize their facilities as to afford the public the various services that it needs, with convenience and economy.

Several committees have been actively engaged in studying various phases of the inductive interference problem, some being joint committees formed upon the invitation of state regulatory bodies, others being established by groups of public service companies. The purpose, in general, has been to develop a more comprehensive understanding of the subject and to make available systematic working principles and standards for guidance in field practise.

In this direction, perhaps the most prominent work of national scope has been done through the cooperative efforts of the American Telephone & Telegraph Company representing the Bell Telephone System, and the National Electric Light Association. A joint committee of these two interests is conducting studies for the purpose of preparing comprehensive principles and practises of coordination for the guidance of the associated operating companies in planning the location, construction and operation of their facilities. Two progress reports thus far issued embody rather complete principles of inductive coordination and encourage the expectation of further constructive results toward solving the inductive interference situation.

On all sides there is a growing realization of the importance of maintaining a broad view to the future and of consulting cooperatively in advance on the development of plans for contemplated plant extensions.

The committee has not learned of the advent during the year of any outstanding new devices applicable to the prevention of inductive interference.

AUTOMATIC TELEPHONY

The further installation of automatic telephone exchanges has continued during the past year. At Omaha, Nebraska, a panel automatic plant was placed in service in December, 1921. During the year automatic exchanges have been built in accordance with predetermined policies as to design. There is, however, nothing particularly new to report in the way of engineering change.

PRINTING TELEGRAPHS

The Western Union Telegraph Company has continued to increase the number of its circuits operated by multiplex printer methods. In many places all of the circuits operated into an office are "printer"—no manual Morse circuits being worked at these points. The extension of printing telegraph systems has necessitated opening additional repeater stations, but this is an economy in view of the increased volume of words in a given time which may be handled over a wire properly spaced with repeaters.

During the year the Postal Telegraph-Cable Company once more has placed a printing telegraph system in service on certain New York-Chicago circuits. The system is the Morkrum Multiplex. The Postal Company has been operating manual Morse exclusively since early in 1919, at which time the printer duplex system then in use was discontinued.

RADIO TELEGRAPHY

Trans-oceanic commercial radio telegraphy has continued to improve in reliability, with the natural result that the volume of traffic has steadily increased. Radio duplex channels now are continuously operated between New York and stations in England, France, Norway, Germany, with stations soon to be opened in Sweden, Holland, Italy and Poland. The station of the Radio Corporation of America, at San Francisco, works continuously with stations in Hawaii and Japan.

A noticeable tendency is to employ vacuum tube oscillators for transmission, both for telegraphy and telephony.

On the Pacific Coast continuous radio telegraph service is performed by a commercial company between the cities San Francisco, Los Angeles, San Diego, Tacoma, Portland and Seattle. A large volume of business is handled in competition with the wire companies.

RADIO TELEPHONY

One of the most spectacular developments during the year has been the application of radio telephony. This art has advanced rapidly, along technical and scientific lines for several years, and today many startling demonstrations, of special circuits, instruments of high sensitivity, special amplification and accurate modulation are in use. This valuable scientific work has of course been continued, but the committee wishes to report, this year on the engineering development of the art.

Although several scientific developments and inventions could be recorded the great work has been the extensive application of radio telephony, increase in efficiency, power and quality of transmission, and the increase in efficiency and simplification of receiving equipments to meet the great demand of the general public for telephone reception in the home.

The regular public broadcasting of news, church services and entertainment from the Pittsburgh district created nation wide interest in radio broadcasting and within the year the manufacturers and distributors of radio apparatus have started additional regional broadcasting service from large radiophone stations, giving news, music, speeches, church services, grand opera, athletic events, market reports, etc.

The fascination and value of radio telephone broadcasting service in the city, home and on the isolated farm has created such a demand for telephone receiving equipment that an active industry has grown up within the year.

The design and production of high efficiency instruments suitable for the novice, with simple operation, and suitable in appearance for the living room, has been an engineering development worthy of note, and it is felt that the great activity in this art justifies the present extensive engineering development to meet the large future application of radio telephony.

RAILROAD TELEGRAPHY AND TELEPHONY

Plans for additional railroad intelligence transmission reflect the general interest in radiophone developments. Operating departments have expressed a need for a simple, reliable and comparatively inexpensive radiophone equipment. It is anticipated that such sets will have a field in train operation for communication between caboose and engine. Today railroad trains a mile long are quite common and there is a positive need for communication between conductor and engineer on such trains.

Also there are possible applications for portable radiophone sets for use in bridging gaps temporarily when washouts or floods destroy pole lines carrying wires.

At large seaports the railroad companies maintain extensive fleets of tugs and it is found that radio telephony affords an opportunity to maintain continuous communication between tug captains and tug dispatchers.

The Telegraph and Telephone Section, American Railway Association during the year completed reports dealing with "Telegraph and Telephone Transmission," "Wire Crossings," and "Education and Training of Telegraph and Telephone Employees."

A technical development of the year was the introduction of a vacuum tube rectifier used to transform alternating current into direct current at 80 to 400 volts.

AERIAL CABLES

Further extension of the aerial cable plant of the American Telephone and Telegraph Company includes a section between Harrisburg and Pittsburgh, Pennsylvania, a distance of about 200 miles. This cable provides approximately 300 telephones and 175 telegraph circuits.

SUBMARINE TELEPHONE CABLES

On April 11, 1921, commercial telephone service was inaugurated between the United States and Cuba, over three submarine cables laid across the Florida Straits between Key West, Florida and Havana, Cuba. These submarine cables are the longest and most deeply submerged which are in use for telephone communication. The cables are 104.9 nautical miles (195 km.) long. These cables are loaded and vacuum tube repeaters are employed at the terminals for connecting land lines to the cabled circuits. In addition to the telephone facilities provided, conductors in the cable are used also for direct current telegraphy and for carrier current telegraphy—over the latter four-channel multiplex printers may be operated.

PNEUMATIC TUBES IN TELEGRAPH SERVICE

In large cities it becomes necessary to establish branch offices in addition to the main telegraph office, so that the public may have convenient access to the telegraph. In the business districts the volume of traffic at some branches, if handled by wire, would necessitate the use of a large number of circuits to the main office with operators at both ends of each circuit, in order to move the traffic promptly under normal load conditions. To handle peak loads or abnormal rushes would require additional wires, equipment and operators, that would be idle a greater part of the time.

This has led to extensive use of underground pneumatic tubes between the main office and the more important branch offices. Tubes are generally laid in pairs in order to handle traffic in both directions simultaneously. While the initial installation is expensive, the annual charges are found to be less than the cost of handling large numbers of messages by wire.

The load limit of a tube is seldom reached, even during abnormal peaks, since the power required to move the carriers containing messages is a small part of the total power required to move the carriers and the air column in the tube. Approximately constant speed of service can be maintained under varying traffic conditions. In addition, chances for errors in receiving and in re-transmitting the message are eliminated.

Tubing of 2¼ inches inside diameter has been standardized as most suitable for telegraph service. The terminal equipment and carriers are not too bulky, yet the carriers are large enough to contain a considerable number of messages. Outbound tubes are operated under pressure and inbound under partial vacuum, the power supply usually being at the main office end.

The outer ends of a pair of tubes are joined together to permit the circulation of the same air repeatedly. This tends to reduce condensation in the tubes, and, in case of stoppage, allows pressure to build up behind the carrier at the same time increasing the degree of rarefaction ahead of it.

Power is supplied by reciprocating air compressors for large systems, and by rotary pressure blowers for small systems. Compressors are driven by electric motors through short belt drives with idlers. Rotary blowers are usually mounted on sub-bases with their driving motors and connected through special worm gearing. Compressor systems are operated at 5 to 10 lb. gage pressure and 10 to 18 inches of mercury vacuum. Blowers range up to 3 lb. pressure and 6 inches vacuum. Separate blowers are used for each tube pair with "start and stop" control of the motor to reduce power consumption.

STANDARDIZATION

The Report of the Standards Committee, last published, contains for the first time a representative list of terms and their definitions employed in communication engineering. Most of these definitions were prepared through cooperation of members of the Telegraphy and Telephony Committee serving on a subcommittee.

The terms now incorporated in the published report constitute a good start along this line of useful work, and the present year's sub-committee will undoubtedly add many more definitions so that in time the communication section of the Report will contain most of the terms which are of a permanent nature.

FUTURE ACTIVITIES

A year or so ago a project was submitted to the Board having in view the compilation and publication of a Bibliography of communication literature, the work mainly to be done by members of the committee. Actual work on this undertaking very likely will be delayed pending the return of more favorable printing costs.

It is noteworthy that practically all of the technical papers procured for presentation at meetings have come from members in the New York district, notwithstanding that all sections of this country and Canada are represented on the committee. It is hoped that chairmen of the various Sections will in future encourage communication engineers in their territory to prepare papers for Section presentation and for printing in the JOURNAL. Naturally, those members who regularly attend meetings of the committee are prevailed upon to contribute or procure papers of interest. However, members remotely removed from New York should recognize the fact that papers sent in from the field are particularly welcome and should be forthcoming. It is of serious importance that members of the Institute in all sections of the country have the opportunity to present papers at meetings and that the best of these should be published in the JOURNAL. To this end it is desirable that telegraph, telephone and radio engineers take more active interest in Section meetings.

DONALD MCNICOL, *Chairman*

INSTRUMENTS AND MEASUREMENTS COMMITTEE

To the Board of Directors:

The following report for the year summarizes briefly the activity of the committee, a reference to articles dealing with new or essential instruments and measurements, and a brief description of new apparatus for electrical measurements that may have been designed and developed during the past twelve months.

During the year there was very marked activity abroad in the matter of standardizing rules for instruments. Several instrument specifications have been issued as follows:

England. The latest Standard Specifications of the Engineering Standards Committee are: for Indicating Instruments, No. 89, 1919, for Instrument Transformers No. 81, 1919.

France. A Proposal for Standardization of Electrical Measuring Instruments, Instrument Transformers, and Shunts was prepared by the Technical Committee of the "Chambre Syndicale des Constructeurs de Gros Materiel Electrique" and was adopted by the Chambre on Jan. 20, 1921. These rules appeared in the *Revue Generale de l'Electricite* of May 28, 1921.

Germany. Rules for Electrical Measuring Apparatus proposed by the Verband Deutscher Elektrotechnicker were published in the *E. T. Z.* of Mar. 31, 1921. Those for Instrument Transformers on Mar. 3, 1921, with changes and additions on July 28, 1921. It is proposed that these become effective July 1, 1922.

The French and German specifications were translated by Mr. H. B. Brooks of the Bureau of Standards and copies were circularized among the members of this committee and other individuals throughout the country who might be interested in the subject.

A comparative analysis of the foreign specifications shows some lack of agreement among the different countries. Apparently the rules are not to be considered final; many admittedly tentative parts are included, awaiting revision in the light of further research or practical experience. In general the rules take up questions of construction, accuracy and nameplate markings. Grades are established and requirements prescribed which apparatus must satisfy in order to be entitled to use the grade symbols. These requirements involve considerations of case protection, scale and pointer construction, damping qualities, sensitivity to disturbing influences, insulation, safety, self-heating, standard-ranges, transformer ratios, potential drops in shunts, limits of error, identification of terminals, connections, etc.

Incidentally this standardization has involved questions of terminology, definitions, the setting of standard quantities such as temperature and frequency and the conditions under which tests were to be carried out.

In view of the activity abroad along the lines of standardization for instruments, there was considerable discussion in meeting and correspondence by this committee as to the possibility of preparing similar American rules and the ways and means for preparing and accepting them. It was finally decided that a subcommittee be appointed to canvass the sentiment, particularly of the manufacturers of instruments in this country, as to the necessity or desirability of such standards. Mr. H. B. Brooks volunteered to conduct such a canvass inasmuch as he intended to visit many of the instrument makers in this country. He was, therefore, appointed a subcommittee of one to make such a canvass and report back to this committee. This trip is still in progress and no report is available at this writing.

The committee devoted considerable time in meeting and correspondence to the consideration of standardizing certain terms of measurements and instruments relative to which there was a divergence of usage. The findings of the committee were discussed with the subcommittee of the Standards Committee on Meters, Instruments and Instrument Transformers. It was felt that the particular terms in question represented only part of a large number that might properly be considered. The matter is, therefore, held open for further consideration and action.

The committee feels that report can briefly be made of the following instruments or devices which have appeared during the past year, some of which are novel in principle and others that may be considered modifications of an old principle, applied in a different manner or placed in a more practicable form of instrument. A new design of current transformer called a "two-stage" transformer, consisting essentially of the usual primary and secondary winding and an additional secondary compensating winding to correct for the ratio and phase angle distortions encountered in the ordinary type of two winding transformer, was advanced. This transformer is being designed and developed with a view to improving the accuracy of current transformers for use with instruments and watt-hour meters. A paper by H. B. Brooks and F. C. Holtz is scheduled for presentation, which describes in detail the design and performance characteristics of this transformer.

In response to the demand for a simple inexpensive equipment for testing current transformers, numerous arrangements for making such tests have been developed. Although several of these methods are comparatively old, none has come into general use because of certain limitations, such as time required, insufficient accuracy and lack of robustness. Some of these methods utilize deflection instruments, and others employ integrating instruments for measuring the quantities involved. On the other hand, all of the precision laboratory methods now in use for measuring the constants of current transformers are based on null methods.

Dr. F. B. Silsbee of the U. S. Bureau of Standards embodied the null measurement principle in a simple method for the comparison of two-current transformers of the same nominal ratio. The method is described by him in Scientific Paper No. 309 of the Bureau of Standards. A current transformer testing set embodying the principle of Dr. Silsbee's is now available. The ratio and phase-angle of the transformers being tested are determined by comparison with a standard transformer, the calibration of which has been determined previously by some absolute laboratory method.

What the instrument actually measures is the differences in ratio and phase-angle between the transformer being tested and the standard transformer. It is important to note that the instrument measures differences because difference measurements can be made with much greater accuracy than absolute measurements.

One of the makers of recording instruments reports the development of a new movement in a round chart electrical recording instrument, consisting essentially of a coil acting as a solenoid with the core located in a horizontal position in the center of the coil and supported on knife edges so that its motion backward and forward in the coil varies as a current flowing through the coil varies. Claim is made from tests on these instruments that a greater degree of accuracy is to be obtained over the entire scale than was formerly obtained with the similar design consisting of the movement of two coils attracted to one another. This new design is developed in recording voltmeters and ammeters.

Various devices have been used for some years to indicate phase rotation on polyphase circuits. Arrangements of a more or less complicated nature have been made up and used locally by various operating companies to serve this purpose, but during the past year a manufacturer has developed and placed on the market a phase-sequence indicator. This is a device in small compact portable form, consisting essentially of an arrangement of coils operating on a single lamp as an indicator. A set of directions accompanies the device, so that by two trials in connecting the binding post to a polyphase circuit, the phase rotation can be determined.

Current transformers for laboratory and portable use of the through type, permitting the threading of one or more primary turns, have been available for sometime. During the past year, however, one of the instrument makers has developed a current transformer of this type with additional self-contained primary connections which can be varied through a certain number of combinations giving an extremely wide primary range of current from 10 to 800 amperes. This transformer has, primarily been designed and constructed to give results of a better degree of accuracy than can be obtained from other preceding types of portable current transformers of this type.

The continuing necessity for an electrostatic type of voltmeter is referred to in an article by E. H. Rayner in the *Journal of the Institution of Electrical Engineers* (British) of January 1921. Description is given of a precision form of Kelvin electrostatic voltmeter. Several mechanical and structural changes have been made in the new type of instrument with a view to eliminating known limitations and to increase the range and precision of the instrument.

One of the manufacturers reports the development of a portable frequency indicator, self-contained in a carrying case comparable with the remainder of their line of portable instruments. The armature circuit has two branches, one unaffected by changes of frequency, the other approximately resonant at normal frequency. The scale covers 90 angular degrees and gives an effective range of 55 to 65 cycles.

In the same line of portable instruments referred to above is a self-contained capacitance meter. This consists essentially of a standard condenser mounted in a case and the condenser or capacitance to be measured is compared with the standard by an armature construction equivalent to that of the power factor meter.

The very considerable activity in the field of radio transmission and reception has stimulated the design of instruments, particularly adapted to the quantities encountered in this field. Without endeavoring to list here all of the small low priced instruments for current and voltage measurements in connection with wireless equipments, developed by various manufacturers which have been placed on the market recently, reference is made to one or two devices only which seem new in principle or new in construction.

A standard radio wave meter has been designed and constructed by the radio section of the Bureau of Standards and this instrument, when calibrated, will be capable of measuring wave lengths from 65 to 85,000 meters, or in terms of frequency from 3500 to 4,600,000 cycles per second. A new type of standard inductance of the astatic principle has been developed and placed on the market.

In the field of electrical instruments for boiler or chemical measurements are the following developments. A new conductivity cell has been developed for direct insertion into a boiler drum in order that the concentration of salts in a boiler may be easily determined. The cell is constructed in such a manner that it may be safely used on pressures up to 300 lb. per sq. in. The electrodes are made of heavy nickel and the insulating structure is practically unbreakable.

The concentration indicator used with the cells may be calibrated in total dissolved solids or chlorine content. Calibration is made for the average operating pressure so that the effects of temperature variations are minimized. The advantages of this new cell are due to the elimination of sampling methods and of the necessity for extra piping to the boilers.

A thermocouple for direct insertion into a boiler under pressure has been developed. It may be installed at almost any point in the drums or headers and will safely withstand pressures up to 300 lb. per sq. in. Preliminary tests indicate that it is reliable and accurate. It is expected that this new thermocouple will be found useful for measuring variation in temperature throughout a boiler under varying loads.

A new recording meter for measuring acidity and alkalinity of boiler feed water has been recently developed. The method of measurement is based upon the determination of the hydrogen ion concentration of the feed water. The recorder operates on the potentiometer principle and records the voltage existing between two electrodes immersed in the feed.

The most important feature of the apparatus is the ability to measure actual acidity as distinguished from the total acidity determined by the usual titration methods. Actual acidity depends upon the hydrogen ion concentration and is one of the important factors involved in boiler corrosion. Another great advantage lies in the ease with which the recorder can be utilized to automatically operate signal lights or alarms to indicate undesirable conditions of the feed. Experiments are under way to determine the value of such apparatus used in conjunction with automatic valves to control the amount of alkali added to feed water, and thus maintain the alkalinity of feed within certain limits.

Considering methods of measurements rather than specific devices which may have been under consideration during the past year, reference should be made to the continued activity in analyzing and discussing methods of calibrating instrument transformers. A significant appreciation of the inherent errors in current and potential transformers is growing throughout that part of the electrical industry using instrument transformers for accurate measurements. This is confirmed by the continued development of apparatus for checking current transformers, one being referred to elsewhere in this report. Some of the central stations have equipped their testing and standardizing laboratories with instrument transformer checking equipments, these being, in general along the lines recommended and used by the Bureau of Standards. The equipment is essentially a potentiometer method, based on standard resistances and provides an extremely accurate and rapid means for calibrating instrument transformers over their entire range. It is a laboratory equipment and is not applicable for use in the field.

During the past year there appeared an article by Messrs. J. R. Craighead and C. T. Weller in the *General Electric Review* of July 1921, analyzing the advantages and limitations of the watt-hour meter method of testing current transformers for ratio and phase angle.

At the suggestion of President McClellan, inquiry has been made by your committee of various individuals in the field of activity covered by the scope of this committee for suggestions of future line of research and investigation. Two lines of activity have been indicated.

There is apparently a demand among the central stations for an accurate and ready means of determining the character and extent of faults in cables and after the fault has been determined by measurement, there is need of some form of apparatus, preferably portable in character which will localize the fault so as to permit the cutting out and repair of the faulty section of cable. It is possible that some of the apparatus for all of the foregoing necessities falls outside of the scope of this committee. However, inasmuch as part of the problem involves measurements to determine the fault, it is advanced here as a matter of record.

In this connection reference should be made to the method of locating faults in underground cables described by Mr. Luigi Selmo in *L'Elettrotecnica* December 5, 1921. It is stated that this new scheme, tested recently, has been found very satisfactory in locating faults on the lines of the Societa Napolitana per Imprese Elettriche. The method has the great advantage of simplicity requiring only the use of two commercial type a-c. voltmeters (for instance, the hot wire type) which do not require any special instructions to set up and are easily read.

The other subject which was advanced for continued investigation and research is the question of the measurement of high potentials, particularly in view of the recent rapid increase in potentials in commercial apparatus in connection with the high voltage transmission lines. The committee does not, of course, overlook or ignore the considerable amount of very excellent work which has already been done in this direction, but with the steady extension of the previous limits of commercial voltages there arises a definite need for continued and extended activity to provide practicable, simple and accurate means for measuring these potentials.

F. V. MAGALHAES, *Chairman*

LIGHTING AND ILLUMINATION COMMITTEE

To the Board of Directors:

The Committee herewith submits its report in two sections—first, activities of the Committee, and second, progress in the art.

ACTIVITIES OF THE COMMITTEE

The Committee was appointed about the middle of October. Early in November, a "correspondence meeting" was held, by which the views of the Committee were obtained on subjects which appeared important to the Chairman. This was followed by a meeting at the Association's headquarters. At this time, the plans for the year were finally agreed upon and arrangements made for carrying them out.

ILLUMINATION ITEMS

The principal innovation of this year's Committee is the inauguration in the JOURNAL, of a section under the heading "Illumination Items." It is the purpose of this section to set before the membership, brief articles of interest on topics falling within the field of this Committee. It is the hope of the Committee to supply, through this channel, comprehensive, up-to-date information, in such form as to make it of greatest value to practising electrical engineers. Among other things, it is the intention to review, briefly, valuable material from other sources, which, in its original form, is too specialized or voluminous for the convenience of engineers who do not specialize on lighting.

Mr. W. M. Skiff has undertaken the compilation of material for the Committee. This section was initiated with the issue of February 1922, and already quite a number of favorable comments have been received. In the three issues published to date, the volume of text is as follows—February, page 149, six columns; March, page 223, five columns; April, page 278, five and one-quarter columns. Material in excess of the requirements of the May issue is in the Editor's possession.

In connection with this activity, the Committee has undertaken to supply the Editor, at his request, with "fillers" on lighting to be used at his discretion.

GENERAL MEETINGS

Dr. B. E. Shackelford was designated to take charge, for the Committee, of any arrangements for papers to be presented before General Meetings of the Association. A paper on "Glare" was presented at the Niagara Falls convention.

SECTION AND BRANCH MEETINGS

The Committee stands ready to cooperate, so far as practicable, with sections and branches in arranging for papers on lighting. An announcement has been made in the JOURNAL, but on account of lateness in the season, it is not anticipated that much will be done during the current year.

LIGHTING PROGRESS

Lighting along with other activities was slowed down during the year 1921, due to business depression. While the lamp consumption was within 80 per cent of that of the previous year, the demand for construction materials fell off considerably more. Under the circumstances, the energies of manufacturers were naturally toward the disposal of existing stocks, rather than toward the development of new devices. The magnitude of the use of electric lighting is best indicated by the sales of incandescent lamps. In 1921, one hundred and sixty-six million large, and ninety-five million miniature lamps, were sold in the United States.

While practise in the lighting of commercial and industrial interiors is tending strongly toward general lighting from overhead locations, there are certain conditions where local or temporary lamps are required.

To meet these conditions, there has been developed a new type of mill type tungsten filament lamp, which is somewhat more substantial than any of its predecessors. Utilizing similar principles of construction, some new or improved sign lamps have also been developed. Considerable improvement has been made in the construction of the incandescent lamps for motion picture projection, and it is reported that over one thousand theatres are now so equipped.

For several years there has been under way, a development for providing a more convenient means of hanging fixtures, so that by means of a plugging device, they could be put up and taken down by novices. Since standardization is a prime requisite for such a device to insure interchangeability, an especial effort has been made to bring various inventors together. It is understood that such interchangeability devices are about to be made available by the various manufacturers of wiring devices.

This development led to the contradictory expression "removable fixtures," and the Illuminating Engineering Society has proposed the term "luminaire" as a substitute for "fixture," "lighting unit," etc.

There has been a number of developments in luminaire or fixture design. There is a marked tendency to use enclosed semi-indirect equipment, to facilitate cleaning. Also there is an increasing use of more or less dust-proof enclosing globes. The shape of such globes is tending to the flat or squat forms, in order to increase the vertical components of light and reduce the horizontal.

A number of new color-matching equipments have been designed, adapted to particular applications. There are indications of an increasing use of diffusing glassware in industrial lighting. The equipment requiring round bulb lamps is still in favor for home lighting, although some new developments, taking diffusing glassware, appear very interesting.

Not the least important development in regard to lamp equipment, is the movement toward the standardization of mechanical parts and dimensions of fixtures and glassware.

That there has been considerable activity in the installation of street lighting, is evidenced by the report that a leading manufacturer sold about 15 per cent more equipment in 1921 than in 1920. An investigation reported during the year, gives an indication of the importance of good illumination as a preventative of traffic accidents.

The general tendency has been toward better street lighting with more or less ornamental units, of which the single globe upright has been predominant. Better means have been devised for maintaining attractive appearance without sacrificing the effectiveness of light distribution. Among the important means to this end has been the use of rippled or prism glassware (with or without refractors) so arranged as to diffuse the light without largely modifying its direction.

Highway lighting is assuming a new importance, since it has been shown to be effective in promoting safety on heavily travelled thoroughfares. Moreover, the expense of such installations and maintenance is moderate, compared with the other features of construction suitable for dense and heavy traffic. Special reflectors are being developed for this service, which utilize much of the light ordinarily delivered outside of the roadway.

Outdoor sign lighting stands out on account of the rapidly increasing quantities of light employed. A year ago, relatively few outline signs were using larger than 10-watt lamps. Now, 25 and 50-watt lamps are common, while 75 and 100-watt lamps are used to a considerable extent in the large metropolitan signs.

Electric lighting of signals in streets, railway crossings and on the railway systems themselves, has made quite an advance.

In interior lighting, no application has fallen farther short of the canons of good practise than the school house, despite the fact that the welfare of the future generation was involved. Educators and others have, during the year, pointed out the need of better lighting, and reports from all sections of the country show a very keen interest in school lighting, in connection with both new and old buildings. The State of Wisconsin is the pioneer in adopting a school lighting code, although the New York Board of Education had already been requiring compliance with the Illuminating Engineering Society's code, in all schools receiving State aid.

The Illuminating Engineering Society's Industrial Lighting Code, referred to in previous reports, has been made an American Engineering Standard. This has resulted in renewed activity in several states which have not adopted such regulations.

Automobile headlighting regulations, based upon the Illuminating Engineering Society's code, are now in force in fourteen states, which represent about 50 per cent of the automobile registration of the country. About 40 per cent of the Canadian automobilists fall under similar codes in the several provinces. As a result of experience in Massachusetts, the requirements of the Illuminating Engineering Society's code has been strengthened.

In the field of research and investigation, much new data have been brought out. Some of the subjects include color temperature, ocular functions, gloss on paper, reflection characteristics of paints, and other surface finishes, refraction and interlaboratory photometric comparisons. New investigations of lighting practise in various classes of interiors have been reported.

The year has been one of activity in matters of lighting education. Lecture courses have been held in several cities and portable lighting demonstrations have been exhibited in a large number of places. An excellent example of a permanent lighting demonstration at the Massachusetts Institute of Technology has exerted a perceptible influence on the practise in that part of the country.

G. H. STICKNEY, *Chairman*

POWER STATIONS COMMITTEE

To the Board of Directors:

The Power Stations Committee was appointed somewhat late in the administrative year, which naturally handicapped its activities. However, the report of last year's committee was so comprehensive and complete that it is probably unnecessary and perhaps undesirable to try to attempt a similar kind of report so soon thereafter.

In past years there has been some overlapping of subjects by committees of the various national societies. In order to eliminate duplication of effort as far as is thought advisable, a group of chairmen of committees dealing with power station subjects in the various national societies was called together at the invitation of President McClellan for the purpose of coordinating their work. At this meeting an informal committee was formed of those present with the Institute Power Stations Committee's chairman as the chairman of this Committee on Coordination.

At the conference it was generally agreed that while the N. E. L. A., A. E. R. A. and A. E. I. C. committees dealt particularly with new developments and their application in electric power and railway fields, with special emphasis on desirable developments as determined by experience, the Institute committee should deal more particularly with the technical and scientific side of the problems involved in the design and use of equipment. When such problems arise in the work of the committees of the N. E. L. A. and similar bodies, the chairmen of those committees will refer such problems to the Institute committee for attention. The agreement of all of the chairmen at the conference to this plan should insure a proper coordination of the work and allocation of the various phases to the proper society. It is the intention in the annual reports of the Power Stations Committee to call attention to some of the more interesting developments described more fully in the committee reports of these other societies. However, such reports are usually not issued until May or June and it will therefore be difficult to embody these references in a report presented to the Institute at its summer meeting. This suggests the desirability of having some of the Institute committee reports presented at a later meeting in the year.

In addition to the above, the committee has aided the chairman of the Meetings and Papers Committee in the selection of papers on power station subjects for presentation before Institute conventions.

R. F. SCHUCHARDT, *Chairman*

MINES COMMITTEE

To the Board of Directors:

During the past year the Mines Committee has arranged for two combined meetings of local sections of the A. I. E. E. and the A. I. M. & M. E. One of these meetings was held in Pittsburgh on April 18th, at which time a paper was presented by Mr. J. C. Damon of the West Penn Power Company under the title of "The Use of Central Station Power in Coal Mines." A number of Bureau of Mines officials were present and the papers brought forth a lively discussion among coal operators and central station men present.

A second meeting was held in May in Chicago where two papers were presented; one by Mr. Clayton of the Illinois Central Power Company and the other by Mr. Adams, Electrical Engineer of Allen & Garcia, Consulting Engineers. Both papers were on the subject of "Central Station Power in Coal Mines;" one based on the viewpoint of the Central Station Company and the other from the viewpoint of the customer. During the coming year it is suggested that the Mines Committee encourage similar combined meetings in other localities.

Owing to the large stocks of metal and the quiet condition of most all of the industries during the past year, both metal and coal mines have been operating at low outputs. A number of the metal mines are, however, taking active steps to get started again and with the gradual improvement in industrial conditions, both metal and coal mines will enjoy an increase in demand that will be very gratifying. A large number of the coal mines are closed down at this time, due to a nation-wide strike. The large stocks of coal on hand together with the general slack condition of the industries, makes the effect of the strike little felt and unless the strike is soon settled the non-union fields will enjoy a very steady business.

Both metal and coal mines are contemplating extensive changes in application in electric power and in some cases active steps are being taken to place the mines in the best possible condition in respect to the use of power.

The use of central station power for mines is growing in popularity each year and it is now the exception for a mining company to install an isolated power plant if central station power is available. During the war the central station power systems were greatly overloaded resulting in poor service in many cases. Since the war the load has decreased and the central station systems have spent a great deal of time and money in strengthening their lines and improving their service so that very few complaints are now heard regarding poor service from central station power.

Improvements in the use of electric power in mines during the past year have been more or less curtailed and consist largely of improvements in loading machines, the further application of automatic substation equipment and automatic control systems for mines, fans and pumps.

There has been little activity during the past year in regard to car dumpers, coal and ore bridges, shovels and drag lines, but there seems to be an indication of some activity during the coming year.

The by-product coke oven industry has been very quiet during the past year, but there seems to be indications that there will be considerable activity during the coming year. This will give the builders of by-product coke oven plants a chance to take advantage of some of the new schemes that have been recently developed and tried out.

Graham Bright, *Chairman*

MARINE COMMITTEE

To the Board of Directors:

The activities of your Committee have been somewhat affected due to the sudden and serious illness of the Chairman, Mr. Arthur Parker. However, we are pleased to report his gradual return to health.

Your Committee being associated with an industry, (shipbuilding), which received a great impetus during the war, finds itself in a somewhat similar position to that industry. The large fleets of merchant vessels tied up in all parts of the country and the question of disarmament has had a retarding effect on the program laid out by the Chairman at the beginning of the year.

Seven meetings have been held. The first, September 23rd, at which time the Committee was organized, Subcommittees appointed and the following work left from the previous year was undertaken:

1. Work of the Historical Committee.
2. Fixtures, fittings and etc. to meet requirements of the New Marine Rules.
3. Terminal facilities at piers.
4. Joint Meeting with the Society of Naval Architects and Marine Engineers for November 17th.
5. Adoption of Marine Rules by the American Engineering Standards Committee.

The following Subcommittees were appointed:

(a) To further the cause of having the Marine Rules adopted by the American Engineering Standards Committee.
(b) To write specifications for standard appliances.
(c) To detail power apparatus for auxiliary machinery.
(d) Propulsion Committee.
(e) Historical Committee.
(f). Radio Committee.
(g) Joint Meeting with Naval Architects and Marine Engineers.
(h) Wires and Cables.
(i) To have Steamboat Inspection Service include some requirement of electrical knowledge by licensed engineers and a separate electrical license for motorships.
(j) Editing Committee.

The year's work has been rewarded with many successes.

Through the efforts of Subcommittee (a), American Engineering Standards, the Institute is the sponsor body for "Electrical Installations on Shipboard," "Marine Rules." Thus, concluding the labors of our Subcommittee. President McClellan appointed our Subcommittee as an organization committee for the Institute to form the American Engineering Standards Committee and the work has progressed very satisfactorily and it is believed the Committee will be organized this Institute year.

Standard Appliance, Subcommittee (b), has completed specifications for feeder, junction and branch boxes:

Conduit and conduit fittings.
Fuses.
Receptacles, plugs, switches, non-watertight.
Receptacles, plugs, switches, watertight.
Bulkhead and conduit terminal tubes.
Steamtight fixtures and fittings.
Electric air heaters.

It is the intention to have these specifications incorporated in the reprint of the specifications and some arrangement made for the testing and approval of the appliances.

Power Apparatus Subcommittee (c), in addition to collecting data from the increased number of motor driven auxiliaries on shipboard and the advent of the motorship, where all auxiliaries are motor driven, making much data available, was assigned the duty of bringing the Marine Rules up to date so that when the American Engineering Standards Committee was formed, these suggested revisions would be available for their consideration, and this work has been concluded.

The Propulsion Subcommittee (d) has concluded the work assigned it, that of preparing "Recommendations for Protection of Electrical Apparatus for Use on Shipboard" and referred to in last year's report and it is the desire to have these Recommendations issued to all those vitally concerned. It is the opinion of your Committee that rules for propulsion machinery should not be prepared until a later date.

The Historical Subcommittee (e) has prepared considerable data bearing on electrical installation on shipboard from very early dates to the present and it is the intention during the coming year to prepare several articles giving the date, title, brief of the article and publication, also, supplement these articles with papers on electric propulsion.

The Radio Subcommittee (f) found that due to the rapid changes, it was thought advisable to revise that section of the Marine Rules. The Institute of Radio Engineers very gladly appointed a committee to assist our Subcommittee with this revision, which has been completed and we take this opportunity of thanking them. This revision will be available for the consideration of the American Engineering Standards Committee.

The Subcommittee (g) Joint Meeting with the Society of Naval Architects and Marine Engineers in New York, November 17th, desire special mention owing to the success attending this meeting. Two papers were read.

"Electric Auxiliaries on Merchant Ships" by E. D. Dickinson, Marine Department, General Electric Company and "Electric Propulsion" by W. E. Thau, Commercial Engineer, Westinghouse Electric & Manufacturing Company.

Both subjects were well presented. The discussions were numerous, long and heated and brought out many interesting facts, the most notable perhaps was in the discussion of Mr. Thau's paper that to date the electric drive had not shown as good economy as reduction gear drive, which was much to the surprise of a majority of those present.

Subcommittee (h), Wires and Cables, has been active in discussion of proposed changes, and, no doubt, the coming year will bring forth some desirable changes in the present specifications, as well as, uniformity in specifications for wires and cables for shipboard work.

Subcommittee (i), Steamboat Inspection Service, is of recent origin. The ever increasing use of electricity on shipboard, on steam driven vessels for economy, and on motorships from necessity suggests the necessity of the licensed engineer being familiar with the subject of electricity, which today is not a requirement for a license. The additional hazard can only be attended with diaster unless the personnel to whom the care of electrical apparatus is entrusted are required to have sufficient knowledge for its proper operation and maintenance.

Editing Subcommittee (j) has about concluded the work prepared by the Subcommittees (b), (c), (a), (f).

I desire to take this opportunity to thank each individual member and the Chairman of the Subcommittees in particular for their good attendance, enthusiasm and untiring effort, and congratulate them for the amount of good work done, particularly, in view of the absence of the Chairman and the lack of interest in the shipbuilding industry during the past year.

The coming year will bring many arduous duties, particularly, to the Subcommittee on Steamboat Inspection Service and it will only be by persistent and studious application that results will be obtained.

Acting for the Chairman, I will repeat the concluding paragraph of his 1920-1921 report:

"It is this thought in particular that I would leave with the Marine Committee for the ensuing year, that good work can only be accomplished through good will, consistant application and real cooperation."

G. A. Pierce, Jr., *Chairman pro tem*

IRON AND STEEL INDUSTRY COMMITTEE

To the Board of Directors:

Reversing Mill Drive Equipment

At present, economic conditions are such that an expansion of steel mills to produce a greater tonnage of steel is not important, and reversing mill electrification consists mainly in revamping present plants. This is either done by installing an electric reversing mill equipment in place of a steam engine, or it may be that the mill itself is obsolete, and the mill with its drive is replaced with electric drive and a new mill. This is usually done in order to replace worn out machinery, or to obtain advantage of lower cost of production. In the last two years, considerable attention has been given to the cost of producing steel and the reversing mill drive has received as much attention as any other type of mill. Considerable cost data are being published from time to time on electrically driven mills, so that it is a simple matter for those who are considering the installation of an electric reversing equipment to determine their cost with a very great degree of accuracy. This is something that has not been available heretofore, due to the difficulty in actually determining the amount of steam an engine takes. Several reversing engine installations have recently been made on the basis of obtaining some very substantial improvements in economy, but no results have been published from their installations, so that it is only natural to infer that the results which they had anticipated have not materialized.

In 1907, the first installation of an electric reversing mill was made in this country. Since 1913, the growth of the electrically driven reversing mill has been rapid, until today there are approximately forty installations in operation rolling all kinds of products. Although there are many features of this equipment which are still retained, the improvements in the design of reversing mill equipments have taken place so rapidly that our present day equipments have an entirely different appearance from those first installed. With each new installation, manufacturers have endeavored to incorporate features which permit the apparatus to perform its duty with greater ease, and thereby reduce the attendance and maintenance. Today, the majority of the electric reversing mill drives, regardless of manufacture, require very little attention, and the delays upon the mill are almost negligible. Attention over the week-end is seldom more than an inspection, which requires the service of one man for only a few hours. This is in quite a contrast to that required in reversing mill engines, including those which have been installed in the last few years. The art of applying electric drive on reversing mills has now reached a point where the capacity and characteristics of each machine involved can be determined very definitely, and assurance given that the cost of attendance and maintenance is almost a negligible item in the total cost of producing steel.

A most important fact was the replacement of a twin tandem reversing engine which drove the first finishing stand, a rail mill, by reversing motor equipment. This equipment was the *first main roll electric reversing drive sold in this country to replace an engine.* It was sold in 1917, and delivered in 1918, but conditions at the user's plant were such as to make it inexpedient to install this equipment until this year.

The motor unit has the *highest continuous* horse power capacity (8000 h. p. 50 deg. cent.) of any electric reversing drive in the world. It was designed to roll the first four of the last five passes on a 105-lb. rail section at the rate of 240 gross tons per hour. The last pass is made in an adjacent mill driven by a separate engine. Although the equipment has not been fully loaded as yet, the mill has rolled at the rate of 198 gross tons per hour of 105-lb. rail, which exceeds all previous tonnage records on this mill. A particularly interesting feature is that this rate of rolling was made with the last finishing stand disconnected from its engine, and connected to the first finishing stand so that the motor was driving both stands and rolling five instead of four passes.

Owing to the depression in the steel industry no new tonnage records were made last year.

There has been some controversy as to whether the motor should be shunt or compound-wound. Both types of motors are giving entire satisfaction, from both a tonnage and maintenance point of view. The motors are built very strong mechanically, on account of the great shock to which they are subjected, and are provided with forced ventilation, as the natural ventilation of such machines would be extremely poor.

This equipment has been developed to such an extent that today it is practically standard, and installations can be made, and mills started in operation at their maximum capacity without any question as to the electrical equipment. In spite of the claims that have been made by some engine manufacturers, the economy of such equipments is so much superior to the engine driven mills that during the last six or eight years almost all reversing mills have been motor driven, and in the rehabilitation of older plants where engineering questions are given proper considerations the electric drive is the only type seriously considered. The ability of the electrically driven mill to turn out tonnage is beyond question, and in certain mills where the time element is of vital importance in providing tonnage, the figures obtained on machines driven by engines have been very materially improved upon.

YARD ELECTRIFICATION

Several of the largest steel plants of this country have under consideration, the electrification of their railroad yards, and considerable study has been given this subject with a view toward settling some fundamentals such as the selection between straight locomotives, storage battery locomotives, or a combination locomotive, using just sufficient battery to operate when a contact system cannot be continuous throughout the yard. The merits of each type of locomotive depend to some extent on the particular plant under consideration, but from a purely economical standpoint, the straight electric locomotive has a considerable advantage over the others. It is true in the case of straight electric locomotives that contact systems such as the overhead trolley line or the third rail conductor, have certain objections in a more or less congested yard with complicated track layout, but there are certain advantages which may or may not outweigh these objections. For instance, full time operation is possible since there is no tying up the locomotives to charge or change batteries, consequently for a given amount of work, fewer units are required; there is no periodic replacing of batteries; and rough usage of the locomotive such as it is very likely to get in steel plant yard service will not result in failure of battery, jars, etc. On the other hand, a locomotive which carries its own source of power has a primary advantage over any locomotive which must collect its power as it moves along. The storage battery has reached a high state of development in the mining industry, and there seems to be no good reason why the mine type of locomotive cannot be enlarged to fill the needs of the steel plant. Part of higher cost of operation over the straight electric machines can be compensated for by charging the batteries during off-peak load periods. The principal disadvantages of a storage battery locomotive, are the high first cost and renewal cost of the batteries, and to a lesser degree, the loss of energy which occurs in the battery.

It seems to be the opinion that third rail construction is preferable to an overhead contact system, due to the interference of any overhead wires or structures with the use of locomotive cranes, which are quite a necessary adjunct to the steel plant. Of the two designs, under-running and top contact for third rail construction, the former seems to be preferable because it is somewhat easier to protect with guards and occupies less space.

The standard direct current voltage for practically all large plants is 250 volts, and it would seem advisable to operate the yard locomotives on this circuit provided generating or converting apparatus can be so located that transmission losses are not excessive. In the event that heavy loads must be handled to a considerable distance from any substation, it has been pointed out that double voltage (500) could be used, and either the motor equipment on the locomotive connected for series operation, or 500-volt motors used which would operate at reduced speed in the 250-volt zone.

For railway work it will be necessary to ground one side of the plant distributing system, and some operating engineers will undoubtedly object to this, but the fact remains that systems are operating successfully with one side grounded. Return feeders on the grounded side will be required in most cases to prevent electrolysis.

Owing to the dull business period during the past year or more, finances have not been available for undertaking electrification work on a very large scale, but it is the present policy to start electrifying small portions of the yard and gradually adding to these portions until eventually electric operation will have been thoroughly tried out and the whole system will be changed over.

Main Roll Motors

In spite of the general depression from which our industrial interests are slowly but surely beginning to emerge, and in spite of the fact that the steel industry throughout the country has reached a point of low production wholly without precedent, a review of the large motors and auxiliary equipment purchased and installed during the twelve months period ending June, 1922, for driving rolling mills makes a very creditable showing. All motors purchased for main roll drives with the exception of those for reversing blooming mills are included in this analysis, whether for use in production of ferrous or non-ferrous metals. The application for rolling non-ferrous materials did not exceed 7.4 per cent of the total, and is but approximately 1.75 per cent for brass and copper.

Three of the large manufacturers of this type of equipment report a sale of sixty-four units with an aggregate normal rating of 97,590 horse power. It is a regrettable fact that the general adoption of a uniform method of rating proceeds so slowly. The Association of Iron & Steel Electrical Engineers has adopted the maximum continuous rating with 50 deg. cent rise in an ambient temperature of 40 deg. cent with a maximum momentary torque guarantee, but with no guarantee of sustained overload capacity.

Sixteen of the above motors aggregating 27,620 horse power were purchased on this basis.

Fifteen more aggregating 28,900 horse power were purchased on the so-called Steel Mill Rating under a guarantee to carry rated load continuously with 35 deg. cent. rise in an ambient temperature of 40 deg. cent. 125 per cent load continuously with 50 deg. cent. and 150 per cent load for one hour with 60 deg. cent. rise.

The remainder, thirty-three, aggregating 41,070 h. p. were purchased on basis of continuous operation at rated load with 40 deg. cent. rise in an ambient temperature of 25 deg. cent. and 125 per cent load for two hours with 55 deg. cent. rise.

This multiplicity of ratings is confusing and every effort should be made toward the universal use of a uniform standard method of rating as, for example, the maximum continuous 50 deg. cent. basis officially adopted by the A. I. S. E. E.

The types of mills electrified during the period under consideration include:

8 motors for Rod Mills	12,070	horse power
3 motors for Bar Mills	4,900	" "
14 motors for Merchant Mills	12,400	" "
4 motors for Cold Mills	1,950	" "
3 motors for Continuous	14,700	" "
Sheet Bar and Billet Mills		
15 motors for Hot Strip Mills	27,720	" "
1 motor for Structural Mill	4,000	" "
1 motor for Plate Mill	4,000	" "
2 motors for Hoop Mills	4,000	" "
2 motors for Sheet Mills	4,000	" "
3 motors for Tin Plate Mills	3,000	" "
1 motor for Tube Mill	1.600	" "
7 motors for Copper and Brass Mills	3,250	" "
Total 64 motors . . . Total	97,590	horse power

It is interesting to note that five of these motors aggregating 15,600 horse power have been installed to replace steam engines.

The tendency toward higher speed with resultant lower first costs, improved power factor and efficiency continues. The successful operation of a 5000 h. p. 450-rev. per min. motor appears to have justified the design and construction of a 5750 h. p. 500-rev. per min. motor included in the above list for driving a Morgan Continuous Sheet Bar and Billet Mill. This is the largest capacity mill motor thus far built for this high speed.

The desirability of adjustable speed drives is still in evidence from the fact that 21 of the units listed, aggregating 35,370 horse power, have provision for adjustable speed control.

Thirteen of these units aggregating 26,970 horse power are of the well-known double range modification of the Scheribius system using an independent high-speed regulating set. This auxiliary set consists of a polyphase commutating machine and a squirrel-cage induction motor which receives the output of the main motor secondary at slip frequency and returns it to the supply system at line frequency. It also impresses on the secondary of the main motor a counter e. m. f. and frequency corresponding to the desired speed of the main motor.

Seven adjustable speed units, aggregating 7400 horse power for two mills, are ordinary direct current machines with shunt field control supplied from synchronous motor-generator sets. This reversion to an earlier type of adjustable speed drive in these two mills was determined largely by the greater simplicity of the direct current motor with shunt field control as compared with the a-c. adjustable speed sets, in spite of the lower over-all efficiency of the former.

Two adjustable speed units aggregating 1000 horse power are of particular interest as they embody some very recent developments. The main driving unit in this case consists of a mill type induction motor with a direct-connected synchronous machine on a common base.

The auxiliary machine consists of a frequency converter driven by a synchronous motor. In the operation of the equipment, no torque is developed by the frequency converter and the driving motor supplies the power for windage and friction of the auxiliary set. In the operation and during regulation, the secondary of the main induction motor is connected to the commutator of the frequency converter and the slip-rings of the frequency converter are connected to the synchronous machine connected to the mill. This machine has the property when driven at synchronous speed, of taking the frequency impressed on the commutator and adding to or subtracting from the line frequency which in this case is the secondary frequency of the induction motor. The voltage delivered at the commutator end of the frequency converter is the same voltage as that impressed on the slip-ring end and as supplied from the synchronous motor. The synchronous machine on the main set and the synchronous driving motor for the frequency converter are excited with direct current.

After starting the main motor in the regular way as an induction motor, the secondary circuit is transferred to the frequency converter. This is done with no field on the synchronous machine and with the frequency converter running at synchronous speed. If it is desired to use a speed other than the normal, the rheostat, in the synchronous machine field is manipulated, putting a field on this machine. This causes the synchronous machine to generate a certain voltage which is transmitted through the frequency converter and impressed on the secondary of the main induction motor. This voltage, according to whether it opposes or helps the generated secondary voltage, causes the set to slow down or speed up. Any speed within the speed range can be obtained by simply adjusting the above mentioned field rheostat giving the desired practical range of speed above and below normal or induction motor speed.

CENTRAL STATION POWER

The use of central station power in the iron and steel industry, stands today as follows: Most of the major steel plants have their own power generating equipment, but quite a number of the large works with coke ovens and blast furnaces as a part of the plant, are using a central station connection and buying a small portion of the electrical energy required by the plant. This condition was brought about in some instances due to the fact that during the war, the power requirements in the mills increased faster than it was possible to secure and install additional generating capacity to take care of same, and it was found expedient to buy sufficient power to take care of these requirements. In other instances a lack of finances, or a higher rate of return on an investment in plant equipment other than power generating apparatus was the reason for central station power coming into the plant, but in all cases where there is a central station connection, it has been found to be a very great asset when a breakdown or trouble occurs in the local plant power houses, and as a matter of fact, it is an additional insurance against a total shut-down of the plant.

In some localities the question of frequency has kept central station power out of the plant. The central station generates 60-cycle power, but many steel plants use 25-cycle power for the reason that the motor equipment for large low-speed mill drives is better adapted for operation on this frequency, and until recently converting apparatus, for securing d-c. power which is essential for operating the mill auxiliaries was not as satisfactory on 60-cycle as on 25-cycle operation. In such localities, the use of central station power would require frequency converters or the changing of the mill equipment to accommodate the higher frequency.

Recent studies and reports on super-power systems have pointed out the advantages to be gained from a conservation and economical standpoint by interconnection, and the large steel plants with central station connections are a step ahead of the others in the super-power plans; however, there is one point to which the central stations which burn fuel to generate power, must sooner or later agree, and that is that they cannot always sell power over this connection, but in the interests of conservation and better mutual relations they should in return purchase some power from the steel plant, when this power can be generated from a by-product which would otherwise go to waste, such as is the case over week-ends when the coke ovens and blast furnaces must maintain uninterrupted operation, while a greater part of the remainder of the plant and the mills are shut down.

Now as regards the smaller steel plants where by-product energy is not available for the generation of power, it is almost invariably the case when these plants are located in some large central station power zone that they purchase the major portion of their power requirements. It is this type of plant that has demonstrated the fact that the steel mills can be operated just as well on 60 cycles as on 25 cycles, and that the central station power is found to be very reliable.

The steel mill engineer has two objections to central station power; its cost, and the hazard of a long line connecting his plant with the source of power supply. Under the first objection, he says that the restrictions or price penalties, under the present complicated rate schedules, when applied to his load, the nature of which is highly fluctuating with moderately low power factor, puts central station power out of discussion. On the other hand the central station power solicitor claims (and that very justly in most cases) that the steel man does not accurately figure his power plant costs, forgetting to take into account the fixed charges against the investment in his plant. However, in the final accurate analysis, it will be usually found that central station power cannot compete in prices with steel plant power, when the latter is all generated from the plant by-products. Under the second objection; the length, type of construction, and territory over which the line is built, carry most consideration in determining the hazard. In plants where duplicate feeders over separate routes and into separate substations can be obtained, the hazard is reduced to a very low point, but in most cases this is not obtainable and it is advisable to have some reserve generating capacity sufficient to handle the vital plant load, such as pumps and hot metal handling apparatus in the event of a line disturbance or service interruption.

THE ELECTRIC FURNACE

Since its inception about forty years ago, the progress of development of the electric furnace has been one of unusual activity, especially the decade 1909 to 1919.

From the date of the first commercial electric steel furnace in this country, April 5th, 1906, with a capacity of four tons, the growth in number and capacity has been continually upward, so that in Januray 1st, 1922, there were 388 electric furnaces in the United States, and 50 in Canada. In maximum capacity this was reached in 1921, when two forty-ton electrics were placed in operation at the U. S. Naval Ordnance Plant at S. Charleston, W. Va.

These furnaces are basis lined and have a transformer capacity of 3300 kv-a. One furnace operates with 24-in. diam. amorphous carbon electrodes, the other with 14-in. diam. graphite electrodes, this giving current densities of 46.8 and 137.5 amperes per sq. inch respectively with the transformers at their maximum output of 21,000 amperes per phase. The relative electrode consumption on intermittent operation is approximately 20 lb. of carbon and 10 lb. of graphite per ton of steel.

During December of 1921, an order was placed by the Ford Motor Company for a 60-ton electric furnace for their River Rouge plant. This furnace will have six 24-in. diam. carbon electrodes and transformer capacity of 9000 kv-a. The year 1921, while not productive of much growth numerically, will be notable principally for the development of large capacities.

After the first development of the induction furnace, which came ahead of the arc furnace, it seemed to be overshadowed by the latter, as prior to 1914 the largest unit of the induction type in the United States was two tons capacity. The inherent low power factor of the furnace and the difficulty of maintaining a satisfactory refractory lining were greatly responsible for this lack of development. In 1914 two induction furnaces of 20-tons capacity were installed, but have not been entirely successful. Special applications of a 2-ton induction furnace have been made in the last two years, and a lining developed which, at last report, has withstood 555 heats. This is exceptional performance. It would be a great mistake to surmise that the retarded progress during the past year foretells any slowing down in electric furnace development. Indeed, it rather lays emphasis on how far and how fast the art has advanced.

ELECTRIC CRANES

The electric cranes used about the up-to-date steel plant represents as much development and as many changes compared with those in plants of twenty years ago as have been made in almost any steel plant equipment. When one considers the cranes of many years ago driven by a square shaft, running the entire length of the building; or a little later, equipped with a single motor and the various motions manipulated through clutches, with the modern steel mill four-girder ladel crane, equipped with the latest electric motors and apparatus, double-bridge drive, sturdy cast steel or structural steel construction, bronze bushed quickly replaceable bearings in place of the old style with babbitt poured in place, and equipped with the various safety devices, it is hard to realize they belong to the same family.

Dynamic braking and the use of additional electric brakes has supplanted, to a very large degree, the troublesome mechanical load brake. Accessibility and interchangeability of parts, the elimination of overhung gears, substitution of either bars or angles for the old style copper span wires, the use of automatic control for motors of, say, 35 h.p. and above, and the development of a control whereby additional speed may be obtained in lowering, and also, a magnified effort towards standardization are among the developments made in recent years.

During the last five years (the last one and a half due to the extreme depression, and the three and one-half years prior to that, to the war and after effects), there has probably been less actual development in connection with electric cranes than there were during the five years prior to that time. The last year has seen very few notable installations made. One of the largest and best known crane builders reporting, "There has been little of importance brought out within the last year or so, but we are working on several propositions that probably, eventually, will be of considerable interest."

The Association of Iron and Steel Electrical Engineers is working on a crane standard which will undoubtedly be recognized as a standard specification throughout the country, for heavy duty cranes.

CONTROL EQUIPMENT

A most important development in magnetic control equipment has been perfected and put on the market during 1921. The design of contractors now makes it possible to obtain a steel mill controller with contacts and arc chutes having such life that it needs no longer be the regular week-end duty of the repair man to renew these parts on the severe service applications. Some plants have experienced the life of such parts to be as much as fifteen to twenty times that of former design. The newer design of contactor has several radical departures from the older type, in that all parts as far as possible are made of punchings, being light in weight and very uniform, instead of castings which are heavier and require considerable machining. The result is a quicker operating switch of greater reliability. These contactors have been combined into standardized lines of magnetic controllers, utilizing the voltage drop relay scheme of current limit acceleration. Some of the advantages resulting from the use of the voltage drop relay system of control may be enumerated as follows:

The voltage drop accelerating system provides a combination of current limit and time element which allows the current limit setting to be high enough to provide torque for the heaviest loads and yet when the load is light and requires less starting torque, the time element will reduce the current and torque peaks to lower values. This prevents unnecessary punishment of motor and machinery during the light load periods.

The torque and current peaks during acceleration are, therefore, more nearly a function of the load than with any other system of acceleration. This feature is particularly desirable for applications requiring variable starting torque, such as steel mill auxiliaries. The time element is obtained by purely electric and magnetic means. No dash pots or mechanical devices are used.

POWER HOUSE EQUIPMENT

In reviewing data submitted by various committeemen, the Chairman feels that this subject is one to be taken care of by the Power stations Committee, in that the developments in the power Stations located in the iron and steel industry, are identical with those of power stations in general, except that in a steel plant operating blast furnaces, the gas engine is used to great extent in place of the steam turbine on account of its higher thermal efficiency and greater flexibility in choice of unit size.

ELECTRIC HEATING

Considering general industrial conditions, the use of industrial heating in the iron and steel industry has made a very satisfactory advance in the last year. The number of installations made shows that the industry is beginning to realize that, while electricity is essentially a high cost fuel, the actual cost of obtaining a desired result may be less when this high cost fuel is employed than when some cheaper heating agent, as gas or coal, is used.

Consideration has been given in one or two cases to the possibilities of electrically heated soaking pits. Several large steel plants have given consideration to the metallic resistor type of furnace for low-temperature heat treatment. In general, however, the possibilities of the metallic resistor type of furnace for work up to a temperature of 2000 deg. F. have not been followed up by the iron and steel industries to the same extent as has been increasingly noticeable in industries manufacturing steel products. This furnace is being used in the annealing of automobile castings and of locomotive parts, such as crank shafts, etc.

ARC WELDING

While, in general, there have been no radical changes in arc welding processes employed in steel mills within the past year, there are indications that welding will be advantageously used in an increasing number of applications in this great industry. Undoubtedly, with but little attention and study, there could be found many new applications in which arc welding could be successfully and economically employed, especially since continued research has revealed new and more desirable methods of metal deposition, as well as new metals and alloys for use in repairing different materials.

It is well known that the repair of worn wobblers, one of the oldest applications of electric welding in steel mills, was formerly accomplished by the carbon arc process used primarily because metal could be rapidly deposited. This process is gradually being replaced by the metallic arc, with which ¼, ⅜ x ½ inch diameter electrodes are used, with current values varying from 300 to 800 amperes. The use of large electrodes and heavy current values is similar to the carbon arc process in that rapid deposition of metal is accomplished, but the use of the metallic arc has the advantage over the carbon process in that a less skillful operator is required to produce reliable welds.

A departure from the more or less standardized practise of using ordinary iron electrodes for building up of worn wobblers and spindles, is that of the use of high carbon steel, recently undertaken with success by different steel companies. There have been instances where old files have actually been used as the steel for the repair of worn wobblers, and when the supply of files was exhausted, electrodes were obtained having practically the same chemical composition. In all cases, the metallic arc was used in the process of repairing.

Aside from the more or less standard welding applications such as the repair of driving spindles, pinions, chipped and worn rolls, etc., the electric arc can be used extensively in the repair of all kinds of machinery in service in a steel mill. Until actually tried, the saving effected by repairing worn or broken machinery by the electric arc, cannot be fully appreciated.

E. S. JEFFRIES, *Chairman*

Some Development in Insulating Materials and Processes in Great Britain with Special Reference to Thermal Consideration

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This paper is intended to show the lines along which the manufacturers of electrical apparatus in Great Britain are dealing with their insulation problems.

Particulars are given of the facilities that have been established for insulation research, and the more important developments in insulating materials and processes employed in the various classes of electrical apparatus are discussed with special reference to thermal characteristics and consideration.

The opinions of British electrical engineers upon certain aspects of temperature rating of machinery as affected by insulation are considered.

Survey of Research Facilities

In 1903 an investigation of the thermal properties of various insulating materials was made on behalf of the British Engineering Standards Committee (now the B. E. S. A.) by the National Physical Laboratory in conjunction with a few of the leading electrical manufacturers. Aside from this, prior to 1914, electrical manufacturers in Great Britain pursued independently investigations in insulating problems, and except for occasional papers presented before technical institutions and contributions to the technical press, rarely made an interchange of experience of mutual interest and importance.

In 1914 the Institution of Electrical Engineers established through its research committee a number of panels for the investigation of certain groups of insulating materials. Similarly the British Electrical and Allied Manufacturers Association appointed a research committee, which has directed considerable attention to a number of insulating problems that were marked as needing immediate inquiry in a census taken among the members of the Association.

The establishment by the Government of a Consultative Committee led in 1916 to the formation of the Department of Scientific and Industrial Research. This department has organized and assisted in the financial support of research associations in various industries in cooperation with manufacturing firms.

Later the Institution joined forces with the Manufacturers Association and established the Electrical Research Committee which obtained grants from the Department of Scientific and Industrial Research and in due course became incorporated in the British Electrical and Allied Industries Research Association (Electrical Research Association).

During this period great difficulty was experienced, due to war conditions, in obtaining adequate supplies of insulating materials, and the Electrical Research Association focussed its attention largely on this problem.

The work of the Association is carried out under the direction of a council operating through sectional and subcommittees. The attention paid to insulating problems can best be judged from the fact that seven out of eleven sectional committees and twenty-three out of a total of thirty-four subcommittees deal with groups of investigations relating to insulation. These groups comprise:—

Fibrous Insulating Materials, including:
  Fabrics untreated and treated.
  Papers untreated and treated.
  Fibres, boards and tubes.
  Varnishes and cements.
  Enamelled wire.
  Rules for conducting electric strength tests.
Composite Insulating Materials, including:
  General research.
  Tooling of composite insulating materials.
Porcelain, including:
  Electrical and mechanical tests.
Mica, including:
  Mica and micanite for commutators.
  Mica for condensers.
  Mechanical properties of mica, etc.
  Micanite.
Insulating Oils, including:
  Chemical, physical and electrical tests and specifications.
Synthetic Resins, including:
  Supplies of constituent raw materials for manufacture of synthetic resins.
  Synthetic varnish-paper boards, tubes, etc.
  Moulded insulation employing synthetic resin.
Dielectrics (in general), including:
  Dielectric losses.
  Thermal resistivity.
  Effect of heat on insulation.

MATERIALS

Most researches, whether carried out cooperatively through the Electrical Research Association or by individual makers and users of insulation, have been directed principally to extending knowledge of the behavior of insulation under varying physical conditions, improving quality, developing more scientific insulating

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Presented at the Niagara Falls A.I.E.E. Convention, June, 1922.

processes, defining the requirements of insulation users, and standardizing the methods of testing materials for the benefit of maker and user alike. A most important development has been the increasing tendency in recent years for makers and users of insulation to cooperate either individually or through the medium of the Electrical Research Association. For the most part insulating materials had in the past been supplied by firms having little knowledge of electrical uses or requirements. Conversely, the user, except a few large firms controlling their own sources of supply, knew very little of the problems that confronted the manufacturer of insulation, especially in such materials as fabrics, varnishes and fibrous sheets. For the purpose of this paper the principal developments that have taken place in processes and materials in Great Britain are grouped according to whether they are employed in connection with:

a. Industrial machines.
b. Turbo alternators and other large machines.
c. Transformers.

Industrial Machines

For machines other than traction, crane and mill motors, Class A materials are employed, *i. e.* organic insulation of cotton, silk and paper, either impregnated or untreated. In addition, however, mica wrappings or linings of similar material are employed to a very considerable extent on the slot portions of windings.

Apart from an improved knowledge of their characteristics and their supply in greater uniformity, no very great advance in quality has been made or can be looked for in Class A materials. Certain improvements that are worthy of some note, however, are briefly as follows:

Pressboard

This name is now given to that fibrous insulating material otherwise known as fullerboard, presspahn, etc. which before the war was made only to a very limited extent in England, the supplies being obtained from America or the Continent.

While materials similar to those originally imported are now manufactured in England to meet the requirements of certain markets, newer types of pressboard have been developed along two distinct lines, having the following characteristics:

1. A soft, porous sheet material made from selected and carefully proportioned mixture of fibres and subjected to a manufacturing process which renders the product as absorbent as possible.

This material is principally used for transformers, but is also applicable to machine insulation. Its great absorbent property is secured at the expense of a comparatively low density and correspondingly decreased electric strength.

2. A dense non-absorbent sheet material, during the manufacture of which the fibers are subjected to a process which reduces them to a semi-colloidal state resulting in a product which is very hard and dense, possessing exceptionally high electric strength and capable of withstanding prolonged immersion in hot oil without loss of mechanical properties.

For most uses up to the present, this material has not been required to withstand temperatures over 100 deg. cent., and for convenience in manufacture it has been prepared from a mixture of fibers containing a large percentage of jute. Owing to its ligno-cellulose character however, jute has the characteristic property of becoming somewhat brittle at temperatures higher than about 100 deg. cent., and therefore, if required to meet more severe temperature conditions than this it will probably be necessary at some manufacturing inconvenience to employ a cotton base to secure improved aging properties.

The following table indicates the principal characteristics of these two types of materials together with those of pressboard of ordinary quality, the test for comparative purposes having been made on 1/32-in. thickness of sheet:

Quality	Density	Breakdown voltage per mil in air after one minute's application	Per cent of water absorption after 24 hours	Tensile str. in tons/sq. in.		Minimum radius bend without fraction after 24 hours in hot oil at 100 deg. cent.
				With Grain	Across Grain	
Soft absorbent . .	1.10	250	110	3.80	3.50	Folds flat.
Dense non-absorbent.	1.43	518	44	5.2	3.80	⅜ in.
Ordinary grade. . .	1.25	300	110	4.60	3.60	⅛ in.

Varnish Cloth

Considerable progress has been made in the manufacture of varnished cloth and in investigating the behavior of this material under working conditions, particularly the well-known phenomenon of the very excessive reduction of the electric strength with increase in temperature which is more marked in varnished cloth than in other Class A materials.

In manufacture, particular attention has been paid to the specially important point of dressing. A controversy still exists on this point, but many large manufacturers claim that a dressing is essential to prevent varnish coming into close contact with the cotton fibers, as it is considered that such contact deteriorates the cloth in that:

1. The impregnated cloth swells and appreciably lowers the electric strength per unit thickness.

2. The varnish within the capillaries of the fiber does not completely oxidize, at any rate for a very long period, and thus also lowers the electric strength of the material.

3. The above-mentioned slow oxidation of the varnish in close contact with the fiber sets free organic acids which attack the fiber and produce serious weakening or so-called "tendering."

Another important consideration is the suitability of the varnishes used. As to this there are two principal considerations, viz., the resin content and the contents of driers.

If the resin content is too high, the cloth lacks flexibility; if too low, the varnish film lacks sufficient strength to withstand tension without serious diminution of electric strength.

As regards the contents of driers this is a matter of supreme importance. For a varnish film to possess a high dielectric strength the varnish must be oxidized as completely as possible. Too low a content of driers causes poor dielectric strength. There is, however, an upper limit of drier content, and if this is overstepped in the slightest degree bad "tendering" of the fabric results. This "tendering" frequently does not reveal itself until several months after manufacture, and it can take place in a batched and wax protected roll in the absence of air. It is thought that in the presence of excess driers, unstable oxides are formed in the varnish film, and that these gradually decompose with the liberation of free oxygen which causes the "tendering." In all cases where "tendering" results the dielectric strength of the varnished cloth is found to be exceptionally good. No knowledge has yet been found as to the effect of such unstable oxides on the varnish film under actual working conditions, but it is quite possible that in a temperature of 100 deg. cent. their decomposition would be accelerated, and that the film might be further oxidized, either with the formation of an acid sticky mass, or possibly of a friable power. In any case there would be considerable mechanical weakening of the cloth which, coupled with the effects of vibration, might bring about a breakdown.

SYNTHETIC VARNISH PAPER BOARDS AND TUBES

Materials of this description have of late been the subject of considerable controversy, and the general tendency is to curtail their use until their properties, particularly as regards absorption of moisture and low surface resistance, are more thoroughly understood. A great deal of investigation in this direction is in progress and the limitations of the materials are better understood.

The uneasiness felt in the use of these materials in Great Britain has been intensified by the fact that during the war many different makes were supplied by manufacturers insufficiently equipped in experience and plant to produce commodities requiring such a high degree of technical skill.

MOISTURE PROOF TREATMENT OF WINDINGS

Much consideration has been given to the most satisfactory method of treating windings and two general processes are in favor, viz: vacuum impregnation and dipping, or surface treatment.

For vacuum impregnation on stationary windings bituminous compounds are generally employed, and for rotating windings a varnish which oxidizes only to a limited extent and contains a large percentage of volatile solvent which consequently hardens reasonably well even although it penetrates into interstices not freely exposed to the air. Under such conditions the difficulties of completely oxidizing linseed oil base varnishes are fully appreciated.

In none of the materials employed in these processes has there been any marked improvement in recent years.

While it is generally felt that Class A materials have nearly reached their physical limits of durability under the temperatures and conditions met with in practise, there is still much knowledge to be obtained which will correlate the results obtained in the laboratory with those of practical experience in service.

TURBO-ALTERNATORS AND OTHER LARGE MACHINES

The tendency has been to employ as far as existing processes render practicable materials of Class B. Some manufacturers do this to a limited extent in the case of stator windings where the materials employed usually consist of combinations of mica with paper or cambric. The volume of mica ordinarily contained in a commercial grade of these materials may be as low as 25 per cent, and as will be seen later this proportion does not compare favorably with that of the insulation practicable on turbo-rotors.

Some other manufacturers insulate the stator windings throughout with mica applied in the form of mica paper tape. With this combination the proportion of mica is much lighter, the thin paper serving only as a support during the application of the mica. Mica silk is also used to a considerable extent and enables the application of a higher percentage of mica to be made.

In the processes of insulation, especially those applied to the slot portions of the windings, every effort is made to compress the insulation to as dense a condition as possible and to eliminate as far as is practicable volatile matter which, apart from a tendency to cause insulation to swell when heated, is liable to condense in the coolest parts of the windings with very deleterious effects to the insulation and risk due to its inflammability.

No effective fire-proof treatment of stator insulation has yet been found, although many investigations are proceeding to this end.

Turbo-rotor windings can be insulated almost entirely with hard-pressed micanite containing not less than 90 per cent by volume of mica. The small quantity of grade A insulation that has to be employed during the assembling of these windings can be disregarded. Further, in supporting the end of the windings an almost non-flammable insulation, such as that prepared from asbestos and synthetic resin, can be used, thus rendering the whole of the insulation of the rotor extremely heat-resisting.

Probably the most marked improvements in the insulation of this group of electrical machinery is the closer technical control and supervision that is now exercised of insulation processes in the shops and the more rigid selection of the insulation materials employed.

TRANSFORMERS

Materials of Class A are to a very large extent used. In oil-cooled transformers the solid insulation usually consists of pressboard or varnish-paper board (micarta). In the core type construction the latter material has hitherto been largely used. There is, however, a tendency now to employ pressboard of the very dense quality already described. This material is found to be very strong both electrically and mechanically at the highest temperatures met with in practise. On the other hand shellac varnish-paper in either tube or board form, as ordinarily supplied, softens at temperatures between 75 deg. and 90 deg. cent., and its electric strength at these temperatures is very low. Dense pressboard does not soften and possesses extremely good electrical characteristics. Tests on a cylinder of this material after exposing to a temperature of 80 deg. cent. for twenty hours and, then to oil at a temperature of 90 deg. cent. for two hours, yielded the following breakdown figures:

Instantaneous breakdown	550 volts per mil.
Breakdown after 1 minute	445 volts per mil.
Breakdown after 5 minutes	400 volts per mil.

These results give a time voltage curve at this temperature of a very favorable character.

A very considerable amount of research has been carried out in connection with improvement in the quality of oil used with transformers. The disastrous effects of sludging noted some twelve or fourteen years ago by large transformer users, led to the discovery of the non-sludging character (when properly refined) of the bituminous base white Russian oils. There was a marked tendency among British users before the war to employ this expensive oil, and when the sources of supply were cut off attention was paid to the refinement of paraffin base oils from other sources which up to that time had not shown such excellent properties. A long series of investigations led to the establishment of methods of testing which are now generally accepted in Great Britain and which are about to be embodied in a specification by the British Engineering Standards Association.

The correlation between laboratory tests on highly refined non-sludging oils and their behavior in practise is not as yet very complete. It is possible that their use affords an unnecessary margin of safety in the case in certain types of transformers, and that somewhat cheaper oils would be satisfactory in transformers where there is a minimum amount of bare copper exposed to the catalytic action, and where there is a minimum amount of oil surface exposed to the air.

A considerable amount of research is being carried out in connection with the temperature characteristics of cable insulation both at the National Physical Laboratory and at the works of various cable companies. The complete results of these investigations are not yet available.

Some Rating Considerations

LABORATORY TESTS AND SERVICE EXPERIENCE

While it is indisputable that the rating of electrical machinery must be based upon the temperature which insulation will withstand, it is becoming appreciated that life tests of insulating materials made under laboratory conditions are of little value as compared with practical experience with the operation of machines under known service conditions and for long periods, and that it is only upon the results of such experience that conclusions as to the durability of insulation can satisfactorily be drawn.

Laboratory tests are of the utmost value in enabling comparisons to be made of the relative properties of different materials and also in the development of new materials and processes. In the past, however, there has been a tendency to attach too great importance to laboratory investigations directed to the determination of the temperatures at which mechanical deterioration occurs and on which temperature ratings should be based. Such investigations have not always taken into account the fact that the surfaces of insulated windings exposed to oxidation are relatively very small as compared with the exposed surfaces of test specimens; and that the rate of deterioration of insulation in the case of windings in service, where there may be a considerable temperature difference between the surface and the cooling air, is likely to differ greatly from that occurring in a laboratory aging oven where no such temperature difference exists. Then again in almost all types of windings the insulation is so completely supported mechanically that any hardening, stiffening or embrittling of its layers may proceed without any attendant risk of failure to a point far beyond that which would appear alarmingly unsafe if such support did not exist.

The increasing tendency for power plant engineers to maintain careful records of temperature performances of their large generator and transformer units will eventually afford data of the utmost value and serve to confirm or amend present ideas as to correct temperature ratings.

TEMPERATURE CONSIDERATIONS

It has for long been recognized, especially in connection with large machine windings, that internal temperatures existed considerably higher than the values which have been adopted as standard limits for many years in connection with the older methods of measurement. The temperature limits now proposed for Class B materials under the new methods of measurement, while apparently higher than the figures formerly recognized, do not actually imply higher internal temperatures than have existed in the past, or than the results of experience indicate as safe.

In those cases where conditions permit the use of materials which withstand high temperatures, all the features of design should be viewed in proper perspective and full advantage taken of high temperature limits if by so doing better all round performance results.

In connection with the tendency on the part of British manufacturers to employ in transformers highly refined non-sludging oils, coupled with the use of dense fibrous materials which will withstand high temperatures without deformation or serious loss of insulating value, it is felt by some that the employment of oil conservators safely permits higher temperature limits both in oil and windings than are permissible without the use of these devices.

RATINGS BASED UPON TEMPERATURE RISE

In the case of industrial machines there is a strongly growing opinion among British engineers that in the rating of electrical machinery the decision of the I. E. C. to establish a basis for comparing tenders by different countries according to total temperature was a mistaken policy, and that temperature rise affords a much more satisfactory means of securing this object.

As already noted in connection with Class B materials the combinations of insulation used particularly on turbo-alternators and other large machines differ considerably in the proportions of organic and inorganic materials that they contain, and consequently also in their heat-resisting properties. It is felt that the present classification is unsatisfactory and should be revised, some differentiation being made in the limits set according to the quality and the position in which any particular type of material is used. For instance the insulation that is possible for rotor windings throughout may be relatively of superior heat-resisting quality to that which is sometimes used on the slot portions of stator windings, which again is, in general, superior in this respect to the insulation on stator end windings.

Influence of Temperature on Insulating Materials Used in Electrical Machinery

BY ERNESTO VANNOTTI
Member of Italian Electrotechnical Association, Milan

Laboratory tests, as well as the condition of machines which have been running a number of years, show that the temperatures that can be withstood without damage to the insulating materials are considerably higher than those prescribed by international rules.

The present values have probably been chosen so as to guard against too high temperatures caused by defective construction of certain parts of the machines.

If exploring coils are placed suitably and with care at the points where overheating is most likely to occur, the value of the permissible temperature, as recorded by the coils, should be 10 to 20 per cent higher than the rules permit, in order fully to utilize the materials of construction. Windings for over 5000 volts should not contain any air pockets.

THE influence of temperature on insulating materials is a question of great importance which is to be discussed by the American commission for the standardization of electrical machinery, to which electrical engineers of various countries have been invited. It is much to be desired that a thorough investigation of the subject might lead to the acceptance of the same standards by different countries, so far as these standards concern the permissible temperature rise compatible with the present state of development in the maunfacture of insulating materials.

The president of the commission of Italian electrical engineers asked me to prepare a paper on this subject. However, I must call attention to the fact that the subject is very extensive and involved, and that causes of heating of the insulated portions of the machines, as well as of the insulating materials themselves, may be exceedingly numerous and complicated. I am therefore unable to enter into a detailed discussion, or to compare thoroughly the properties of the different materials used, but will only attempt to give a general survey and summarize the conclusions, which, it seems to me, can be drawn from practise.

Laboratory tests, and the process of manufacture of different insulating materials and insulated windings have shown that the insulated conductors used for electric machines are capable of withstanding, without damage, temperatures which are appreciably higher than the maximum values laid down by the International Electrotechnical Commission.

This observation is borne out by the fact that insulated current-carrying parts of many machines—the temperature rise of which corresponds to standards approximately in accordance with those now prescribed by the International Standardization Rules—are still in excellent condition after 20 years' service, even in cases when notable overloads occur. In other words, the running of these machines for a long time, which corresponds to a continuous service lasting at least 10 to 20 weeks, with temperatures 20 to 30 per cent greater than the maximum values now allowed by international standards, has scarcely affected the structure and dielectric strength of the insulating material.

Practise has shown, moreover, that machines whose temperature rise, measured by the increase of resistance of the windings, remains within the limits allowed by International Standards, are sometimes liable to failures after a comparatively short time on account of excessive temperature rises which cause failures to occur in parts of the winding. As an example, I may mention the case of a three-phase, 6000-kv-a. turbo-alternator, at 1500 rev. per min., 6250 volts, 580 amperes, 50 cycles. The stator is well ventilated and has bar winding of massive copper as shown in Fig. 1. This winding should have an average temperature rise of 60 deg. cent. according to the method of measuring the increase of the resistance. Nevertheless, the insulation was damaged after a certain time on account of the abnormal temperature rise of the bar placed nearest the air gap. The small iron wedges which partly close the slots of the stator are evidently much too small to prevent or dampen to any great extent the variations of the magnetic field in the copper bars. For this reason, large eddy currents occur which entail excessive local heating and consequent damage to the insulation. The copper bar near the air gap was replaced by a stranded conductor composed of a great number of fine wires. Although the copper cross section was 20 per cent less than the section of the solid copper bar, no further damage occurred to the insulating material under the same operating conditions.

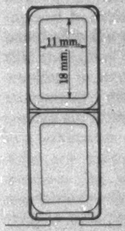

FIG 1.

With high-voltage windings for 5000 volts and over (and occasionally for 3000 volts), it is well known that, if air is present between the individual coils on account of breakages in the insulation, damage is likely to occur as though the temperature rise had been excessive, notwithstanding the fact that the latter is well within the prescribed limits. In this case, the harm to the insulating material is caused by the formation of ozone which is produced by static discharges in the air gaps between the coils.

Displacements of commutator segments have been known to arise, even when the commutator appears to be correctly designed, which entail sparking at the brushes. This occurrence is due to insufficient attention having been paid to the expansion caused by heating.

Presented at the Niagara Falls A. I. E. E. Convention, June, 1922.

It appears, therefore, that abnormal temperature rises, or occurrences met with in practise which are due to constructional shortcomings prejudice the preservation of the insulation in service. Furthermore, it is not always possible to discover these faults or their origin during acceptance tests.

The precise determination of these conditions forms part of the programme of the committee appointed to determine the permissible temperature rises. In my opinion, the existing values have been chosen unnecessarily low so as to insure against concealed faults in construction.

I think that it is pertinent to give an example, which, although not directly related to the subject under discussion, is of certain importance as it serves to confirm my statement that the tendency is to prescribe stringent acceptance tests in order to guard against any unforseen circumstances.

At a meeting of the Italian Electrotechnical Commission the following motion originating with a foreign association was discussed: "Insulation tests for turbo-alternators, contrary to those for ordinary machines, should comprise a pressure test for pressures corresponding to three times the working voltage, since this particular class of machines is most likely to be damaged by insulation failures." I cannot understand the reason for this special treatment of turbo-alternators, and consider that the recorded damage to the insulation is due rather to constructional shortcomings than to insufficient insulation, or to an insulation test that was not severe enough.

In reality, I believe that insulation failures of portions of conductors embedded in the stator iron are caused by excessive local overheating of these conductors, similar in fact, to the case of the 6000-kv-a. turbo-alternator already mentioned. With conductors of ordinary dimensions, that is to say, those having sections sufficient to preclude eddy currents, special precautions have to be taken to prevent local overheating which may be sufficient to cause the best micanite insulation to deteriorate rapidly.

Defects of windings situated outside the stator iron, especially where the conductors leave the iron core, are most probably due to mechanical imperfections, which are easily produced by short circuits or false parallel connections when the end windings outside of the stator core are not properly secured and braced.

I will, therefore, go a step further and assert that the running conditions will be less satisfactory in the case of a machine which has been damaged through one of the reasons just enumerated, and has been rebuilt so as to be able to withstand a test voltage of three times the operating voltage, without altering the principles of its construction. The reason for this is to be found in the excessive thickness of the insulating layers of the parts embedded in the stator which have been renewed with the consequently increased difficulty of ensuring efficient cooling—a problem which has always needed great care with turbo-alternators. If the distance between end connections is augmented in order to allow a test pressure equal to three times the operating pressure to be withstood without reinforcing their supports, the mechanical stresses, damage to the insulation, etc. will be increased on account of the greater distances and higher electromagnetic stresses in the end connections.

I consider, therefore, that the allowable temperature rises prescribed by international standards are too low for machines which are designed and built correctly. These standards, moreover, do not permit the active material of electric machines to be fully utilized, and consequently increase the cost of manufacture.

Moreover, it is logical that excessive local overheating should be objected to and that its cause should be found out during the acceptance tests in order to obtain a guarantee from its after effects. The occurrence of abnormal local overheating can be revealed by inserting exploring coils in places which are most likely to overheat. It goes without saying that these thermo-indicators must be manufactured and put in place with care so as to preclude errors of measurement.

Finally, I should like to make the following suggestions:

1. If the temperature rise is measured by suitably placed and reliable thermo-indicators so that no doubt exists as to the correct measurements of the temperatures at the hottest parts of the machine, new figures should be prepared for the international standards giving the highest permissible temperatures in such cases, the values of which should be 10 to 20 per cent higher than those now allowed.

2. All windings for voltages greater than 5000 volts must be provided with impregnating material in order to prevent air spaces between the individual conductors and the different layers of insulating material.

3. Commutators should be allowed to run at a maximum temperature of 115 deg. cent. provided that no deformation or sparking occurs at this temperature.

The Relation of Overload to the Inner Temperature of Machines

BY GUIDO SEMENZA
Associate, A. I. E. E.
Consulting Engineer, Milan, Italy

OVERLOAD is generally regarded by users of electrical machinery as a convenience. Very few consider the meaning of a rating containing overload allowances (double rating) from the point of view of the comparability of different makes of machines and of the effects that overload allowances may have on the duration of the insulation of the machine. The object of this paper is to show, in an elementary way, the process of heating going on in electrical machines and to consider what is the fundamental difference between single rating (no overload allowed) and double rating (overloads allowed) and to supply a clear and sound basis for an eventual discussion. I shall here only refer to continuous rating and the word machine will indicate generators, motors, converters and transformers cooled by natural ventilation.

If we want to design a model of an electrical machine in order to follow its thermic behavior, we can imagine it as drawn in Fig. 1. M is a mass of iron thermically insulated by a coating K, and leaving open in contact with the air, the surface a b, the diffusing surface. A is a conductor. I the insulation. We shall neglect the representation of the heat produced in the iron, as this does not change the results of this study. In the conductor A a certain quantity C of heat is produced per unit of time and is transmitted across the insulation and the iron mass M to the diffusing surface from which it passes by convection and radiation to the cooling air. If we suppose the temperature t_0 of the cooling air to be constant after a certain lapse of time we shall reach a condition of equilibrium in which all the heat produced in A in a second is transmitted to the air in the same time and therefore all the points of the machine will have reached a steady temperature. In such a condtion if we measure these temperatures we shall be able to plot them in a diagram, more or less, of the appearance of the one shown in Fig. 2. The temperature t_1 of the conductor or heat generator falls across the insulation to t_2, the fall being ruled by a law similar to Ohm's law; the fall of temperature in fact is directly proportional to the flow of heat and to the inverse of the thermal conductivity of the mean. A second fall of temperature occurs in the mass M to t_3 the diffusing surface temperature, and a third on $t_3 - t_0$ the fall occurring between the surface and the mass of the cooling air. The effect of heat generated in the iron mass will be to increase the inclination of the line t_2 t_3. As we have means of measuring t_1 and t_0 and the current in A, we can, in these steady conditions, know exactly what is going on in the machine. If we assume t_0 to be the maximum cooling air temperature, we can at any time in the life of the machine be sure that the temperature of the copper, hence of the insulation in contact with it, will never rise above the value t_1, provided that the current in A does not increase over the rated intensity.

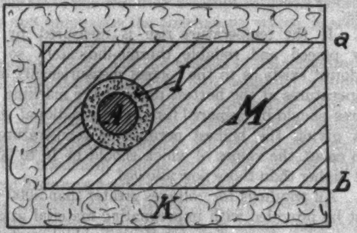

FIG. 1

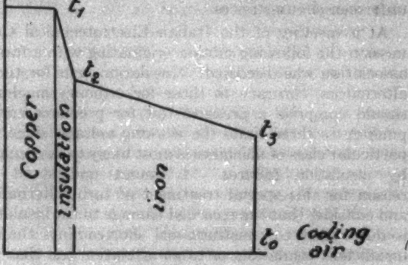

FIG. 2

We can easily realize also that with the same production of heat (that is, losses in the machine) even with very large difference in the thickness of insulation and of the mass of iron we can keep the temperature t_1 of the conductor below a certain allowed maximum, by adapting the area a b of the diffusing surface to the conditions of the special case. A thick insulation (high-tension machine) will give a greater fall $t_1 - t_2$ in the insulation than a thin one (low-tension machine) therefore in order to have t_1 constant, the value of t_3, that is the surface temperature of the machine, will have to be lower in the case of thick insulation, which can only be attained by increasing the diffusing surface. The same may be said for any condition which will increase the internal thermic drop of the machine.

Presented at the Niagara Falls Convention, June, 1922.

Therefore machines of different tension, speed, construction and make can be so designed, that in the steady normal conditions, or in other words, at their rated power, the temperature of the conductors, hence of the insulation, shall never exceed the prescribed value.

Going back to our model let us suppose that a certain steady thermal condition is reached and let us increase by a certain per cent the current in the conductor, so that the production of heat per unit of time would be increased from C_1 to C_2. At the first instant after the increase the thermal flow is still determined by the pre-existing conditions, so that the quantity C_1 of heat is transmitted through the insulation under a difference of temperature $t_1 - t_2$. As in these conditions not more than C_1 can leave the conductor, the extra heat $C_2 - C_1$ is stored up in the conductor raising its temperature from t_1 to t_1'. This allows an increase of flow of heat across the insulation. But if we suppose the insulation is formed by a superposition of very thin layers, each of them, receiving more heat, stores up a part of it in order to increase its temperature before it can increase its transmission to the following layer, and so on. Considering the whole path through which heat is transmitted (insulation and iron) we can say that in the variable period following an increase in the quantity produced, each element in a first period stores up heat then transmits it to the following one, and this process goes on till a new steady condition is reached in which in every unit of time an equal quantity of heat is produced and diffused in the air. For this condition we shall be able to plot a new diagram. Now what it is of interest to know is the new value of t_1 and the time the system takes to reach it. The knowledge of both these elements is necessary. When overloads are stated for a limited period of time it is important not only to know what is the maximum temperature reached, but also if during such period the new steady temperature is reached.

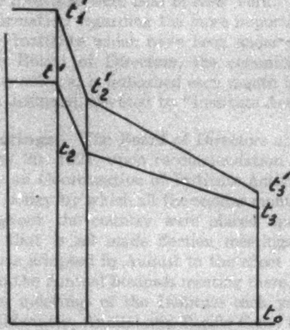

Fig. 3

Many causes may influence the behavior of the machine in this variable period.

First, the thickness and nature of the insulation, or in other words the thermal conductivity of the whole layer of insulation, as upon this will depend the fall of temperature and the length of the variable period.

Then comes the construction of coils. As to transmission of heat, a single bar conductor is something very different from a coil of very thin wire with heavy insulation. Thoroughly impregnated coils are in this respect different from coils merely coated with shellac or varnishes.

The magnitude of the iron mass and its laminated construction with respect to the direction of the flow of heat, have a good deal of importance, and here especially we meet with differences in the storing effect and in the fall of temperature necessary to drive the heat across the mass itself.

Where the heat produced comes to the diffusing surface the temperature of the surface has an influence on the quantity of heat diffused by convection and by radiation; the diffusing coefficient is not constant, but increases with temperature and with the difference of temperature between the surface and the air. This phenomenon, which is from a certain point of view beneficial, is different in different machines.

In conclusion machines of different tension, speed and construction, which at their steady normal conditions of work reach the same rise of temperature in the copper, when overloaded say for one hour with the same percentage of overload, necessarily reach different temperatures in the copper as all the elements by which they differ (insulation thickness, revolutions, power, storing capacity, dispersing surface) have different effects on the rise of temperature. Moreover in some machines the end of the overload period will find the new steady conditions established, in others, especially in heavy machines, this state will not have been reached.

So we may summarize by saying that machines quite comparable at their normal rating for continuous service are not comparable the same percentage of overload imposed for the same period of time.

All forms of rating with overloads (double ratings) in use or proposed up to the present are intended to apply to a large variety of machines, and contain only rough divisions in two or a few classes according to power. If the German rules are excluded (in which it was not question of thermal overload) no mention is made of temperature. The buyer must be satisfied with the seller's declaration that overloads will not spoil the machine.

The aim of an international rating rationally considered is to provide a manner of defining what a machine really is. The buyer must be able to compare offers of machines of different makes and countries by their ratings.

With the single rating he can do it quite well; he knows that a machine rated at 10 kw. will give him 10 kw. in a continuous manner without submitting the insulation to dangerous temperatures. If he wants to overload his machine it is at his own risk. All this is clear, plain and simple.

When a double rating is given in the ordinary forms without stating the final temperature what does the buyer know about his machine? He knows that at the rated power for continuous run, the insulation of the machines will not have to bear a temperature higher than a certain specified value, but how can he compare offers if, as we have seen, the different machines under overload all have different behaviors as to the rise of temperature? How can the buyer be sure of the duration of his machine knowing that high temperatures are dangerous if applied for a certain time, and not knowing anything of the value of such temperatures and of the length of time they are applied?

One conclusion is that the rating of machines for continuous service, without any allowance for overloads (single rating) is a definite and clear specification and constitutes a fair basis for commercial transactions.

A rating given for continuous service but allowing overloads (double rating) could only be compared to the single rating provided it can be demonstrated that the same overload applied to machines of all sizes, tensions, speeds and construction bring practically to the same ultimate temperature and to the same fatigue of the insulation.

That such a demonstration can be given in the actual conditions of the industry is a matter of discussion.

Should the answer be negative then the only solution, when double rating is wanted is to call for the specification of the temperature reached after the allowed period of rated overload.

Report of the Board of Directors

FOR THE FISCAL YEAR ENDING APRIL 30, 1922

The Board of Directors of the American Institute of Electrical Engineers presents herewith to the membership its Thirty-eighth Annual Report, for the fiscal year ending April 30, 1922. A general balance sheet showing the condition of the Institute's finances on April 30, 1922, together with other detailed financial statements, is included herein. The following is a brief summary of the principal activities of the Institute during the year; more detailed information has been published from month to month in the Institute JOURNAL.

Directors' Meetings.—Because of the wide geographical representation upon the present Board of Directors a bi-monthly meeting policy was adopted beginning with October, 1921; meetings of the Executive Committee were held during the alternate months.

The Board of Directors held seven meetings during the year; six of these were held in New York and one at Salt Lake City, Utah. Three Executive Committee meetings were held in New York.

Information regarding the more important activities of the Institute which have been under consideration of the Board of Directors, the committees and the various officers, is published each month in the section of the JOURNAL devoted to "Institute Activities."

Meetings.—The Board of Directors at the meeting of May 20, 1921, upon recommendation of the Committee on Coordination of Institute Activities adopted a new policy by which all the regular monthly meetings throughout the country were placed upon the same basis, that is all made Section meetings. A resolution was adopted in August to the effect that in addition to the Annual business meeting there shall be four general meetings of the Institute each year including the Midwinter, Annual and Pacific Coast Conventions.

Annual Meeting.—The Annual Business Meeting was held at Institute headquarters, New York, on May 20, 1921. The Annual Report of the Board of Directors for the fiscal year ending April 30, 1921 was presented. The Tellers Committee presented its report upon the election of officers for the year beginning August 1, 1921. The business meeting was followed by a technical lecture.

Annual and Pacific Coast Convention.—The combined Thirty-Seventh Annual and Tenth Pacific Coast Convention was held at Salt Lake City, Utah on June 21 to June 24, 1921. Four technical sessions were held, all of them during the mornings, at which fifteen technical papers were presented in addition to the Presidential address, the Technical Committee Reports and an address by the Local Honorary Secretary for Italy. The annual conferences of the Sections Committee were held with an attendance greater than at any previous meeting, forty Sections were represented. The discussions were reported in the August 1921 JOURNAL.

New York Meeting.—The 372nd Institute meeting was held in New York on November 17, 1921. Two sessions were held. The afternoon session was held jointly with the Society of Naval Architects and Marine Engineers and two papers were presented on electric auxiliaries and electric propulsion of ships. The evening session was occupied by a lecture on "World Communication."

Mid-Winter Convention.—The tenth Mid-Winter Convention was held in New York on February 15-17, 1922. Five technical sessions were held at which twenty papers were presented. Thursday evening was devoted to the presentation of the Edison Medal to C. C. Chesney, followed by a lecture on "Colloids." Friday afternoon was assigned to inspection trips and the meeting closed on Friday night with the Annual Dinner-Dance.

Spring Convention—The first Spring Convention of the Institute was held in Chicago, Ill., April 19-21, 1922. Three technical sessions were held at which ten papers were presented. In addition two sessions were devoted to symposiums on subjects of general engineering interest and an afternoon and two evenings were occupied by an inspection trip, theatre party and dinner-dance.

Abstracts of the reports of the chairmen of many of the Institute committees and delegations are included herein under various headings.

Meetings and Papers Committee.—The Committee has obtained during the past year an ample number of papers, both for the two conventions already held and for the scheduled meetings at Niagara, Vancouver and a proposed meeting next November.

The Committee has been reorganized on a new basis to obtain general cooperation of its membership, irrespective of geographical location. Members have been supplied with dockets of papers received, giving author, title, size and contents of each paper, and this has aided materially in reaching conclusions and laying plans.

The Committee has clearly stated to prospective authors the bases for choice of papers, and this has enabled authors to meet in advance the imposed conditions, and has considerably lightened the work of review which falls upon the technical committees. The Committee has also endeavored to solve the question of the balance of technical and general interest matter published in the JOURNAL by having written for each specialist's paper a "story" of the paper which briefly tells of the conditions of the art, the reasons for writing the paper, the new material added by experimental and analytical work, the general conclusions reached—all in language that is found acceptable to executives, and therefore readable to the membership at large.

Condensed into a few words—in the evolution of the affairs of the Meetings and Papers Committee, the endeavors are definitely to further organize, systematize, coordinate and codify.

Committee on Coordination of Institute Activities.—The function of this committee is to consider, investigate and report recommendations to the Board on such matters, involving the interests of more than one of the other committees or not relating to the field of any other committee, as may be referred to it by the Board.

The most important action taken during this year was to recommend a new policy for the publications of the Institute. This recommendation was made in conjunction with the Meetings and Papers Committee and the Publication Committee and was subsequently approved by the Board.

Among other matters discussed by the committee were the organization of the Standards Committee and the determination of a definite policy as to the number and location of Honorary Secretaries.

Publication Committee.—This committee has general supervision of all the technical publications of the Institute and has been active this year in modifying the methods of publication of the JOURNAL and the TRANSACTIONS to meet the general financial stringency. The most important problem before the committee this year was to determine a method whereby the expense involved in printing the TRANSACTIONS in the form heretofore issued could be eliminated. Several meetings of the committee have been held during the year resulting in procedure for publishing the JOURNAL and TRANSACTIONS which has been explained in previous notices to the membership and which is in effect for the 1922 publications.

Sections and Branches.—The growth in Section activity which has been noted in the Directors' Reports of the last few years continued during the past year both as to new Sections organized and number and attendance at meetings as evidenced by the figures given in the following table. The regional Vice Presidents have in many cases visited the Section headquarters in their territories and this has resulted, as it was hoped when the plan of dividing the representation of the Board into geographical districts was instituted, in a closer relation and greater interest of the membership as a whole in Institute affairs.

During the past year Sections have been organized at Columbus, Ohio, Oklahoma and Santiago de Chile. An extension of territory was granted to the Vancouver Section.

The development of Institute Branches has during the past year lived up to the post-war promise of greatly increased scope. This development is recorded not so much in the increased attendance at meetings but by the greater number of schools of all classes from which the student enrollment is now drawn. The work of passing upon these Student applications from schools never before listed has required considerable time on the part of a special subcommittee of the Board of Examiners. New Branches have been authorized at Swarthmore College and Rutgers College.

	For Fiscal Year Ending						
	May 1 1916	May 1 1917	May 1 1918	May 1 1919	May 1 1920	May 1 1921	May 1 1922
SECTIONS							
Number of Sections..........	32	32	34	34	36	42	45
Number of Section meetings held...	251	265	245	217	262	303	373
Total Attendance..	28,553	31,299	34,614	25,837	30,741	37,823	54,378
BRANCHES							
Number of Branches..........	54	59	59	61	62	65	67
Number of Branch meetings held...	360	368	268	156	360	443	439
Attendance.......	15,166	16,107	10,683	6,441	16,827	21,629	25,358

Scholarships.—The governing bodies of Columbia University have placed at the disposal of the Institute a scholarship in Electrical Engineering beginning with the academic year 1922-23 and continuing until further notice. The scholarship pays $350 toward the annual tuition, and reappointment for completion of course is conditioned upon maintenance of good standing. An Institute committee will consider the candidates and make a recommendation to the Board of Directors regarding the award.

Standards Committee.—The Standards Committee has held five regular meetings during the year for the transaction of its business.

The Committee has adopted, subject to confirmation at the May meeting, modifications and additions to various parts of the Rules, including a new chapter on rules for storage batteries adopted provisionally last year. The Committee has also initiated work on rules for electric welding apparatus, which work is now well under way.

The Committee has prepared an unusually complete report on screw lamp-caps and lamp-holders, presenting a complete historical picture beginning with the original designs and extending through the development to the American standard screw-shell base over a period of years.

A report has been completed comparing the rating of motors using Class A insulation in accordance with the various rules which have been suggested in the United States and in England. This comparison shows some important differences, but in view of the fact that the rules for open-type motors employing Class A insulation are still in the hands of the Sectional Committee on Rating, the Standards Committee has refrained from taking any definite action during the present year.

The Committee has arranged for the appointment of an Institute representative on the Sectional Committee on Safety Code for Aircraft and nominated members for the Sectional Committee on Electrical Installations on Shipboard.

A large number of communications covering all branches of its work has been received and acted upon.

Considerable attention has been given to the best method of organizing the standardizing work of the Institute, with particular reference to the Standards Committee, the Technical Committees, the various Sectional Committees appointed under the rules of the American Engineering Standards Committee, and the United States National Committee of the International Electrotechnical Commission. The Committee expects to submit to the Board for approval at its May meeting, a comprehensive plan which will tie these various committees more closely together.

American Engineering Standards Committee.—The following statistical summary of the work of the American Engineering Standards Committee is taken from the report of the committee for 1921.

Member-bodies	20
Organizations represented	28
Representatives on main committee	52
Approved standards	17
Standards up for approval	17
Projects having official status	79
Projects for which sponsorship has been accepted	51
Organizations acting as sponsors	43
Cooperating bodies	160
Individuals on sectional committees	548

The committee is receiving government cooperation through the active participation of numerous branches of the Federal Government in the work of the committee. The committee has a large number of specific projects on hand which are being handled by sectional committees in the regular way. International cooperation is assured through the committees being in touch with the national standardizing bodies of Austria, Belgium, Canada, Czecho-Slovakia, France, Germany, Great Britain, Holland, Italy, Japan, Norway, Sweden and Switzerland. Three new member bodies were added during the year. Additional financial help over that derived from dues from the member bodies was received from companies interested in standardization and through special contributions to the extent of $7425.

The Department of Commerce at Washington has arranged to promulgate standards to be known as Standards of Simplified Practise. At the request of the Secretary of Commerce, the A. E. S. C. has designated Mr. A. A. Stevenson, the retiring chairman of the committee, as a special representative to work with the Department in the cooperation between the Department's Division of Simplified Practise and the standardization work of the A. E. S. C. and a representative of the Department has been designated to act on the A. E. S. C. This arrangement is considered one of the important steps taken by the A. E. S. C. during the last year, providing, as it does, definite cooperation and coordination of the work of the Department of Commerce with that of the committee.

Mr. Albert W. Whitney was elected chairman of the committee for the year 1922.

U. S. National Committee of the I. E. C.—This Committee has held only one general meeting (October 14th, 1921), but the Executive Council of the Committee has held several meetings from time to time. By letter-ballot of the membership of the Committee an amendment in the Statutes of the Committee, the purpose of which was to provide for *ex-officio* representation, in the Committee, of the War Department, the Navy Department, the Bureau of Foreign and Domestic Commerce, "and any other Department of the United States Government interested in the objects of the I. E. C." was adopted. The Departments accepted the invitation, and the representatives designated were: for the War Department, Major General G. O. Squier, Chief Signal Officer of the U. S. Army, and, for the Navy Department, Commander C. S. McDowell, U. S. N. The Bureau of Foreign and Domestic Commerce will also be invited to accept ex-officio membership in the Committee.

The work on proposals to the Commission, suspended last year in order to wait for the report of the A. E. S. C. Sectional Committee on Rating of Electrical Machinery (of which the A. I. E. E. is the sponsor-body), has had to remain in abeyance, because the work of the Sectional Committee has not yet been completed.

The Committee was represented by two delegates at an unofficial conference of delegates of various national committees of the Commission in Paris last November, to consider the difficulties of various kinds which have arisen in regard to the adoption of I. E. C. Recommendations and Rules, in certain countries, since the Brussels meeting of the Advisory Committee on Rating in 1919, and which have forced the Commission to postpone its meetings several times.

The Committee cooperated with the Organization Committee of the International Conference on Electrical Super-Power Systems, which was held in Paris in the week of November 21-26. Several important papers were presented by prominent American electrical engineers. The Committee was represented, informally, at the conference, by Dr. A. E. Kennelly, Mr. F. D. Newbury, and Dr. C. O. Mailloux, who was made Honorary President of the Conference.

National Committee of the International Commission on Illumination.—The work of the U. S. National Committee of the International Commission on Illumination, during the past year, largely centered about the meeting of the International Commission, which was held in Paris, July 4-8, 1921. The U. S. National Committee secured and transmitted for use at that meeting, reports on the following subjects: Lighting Legislation; Automobile Head Lighting; Nomenclature and Standards of Photometry and Illumination; Relative Visibility Function and the Mechanical Equivalent of Light; Heterochromatic Photometry; Use of Light Filters in Heterochromatic Photometry.

The Commission concerned itself chiefly with fundamental definitions, and adopted definitions of "luminous flux," "illumination", and "luminous intensity", which are in accordance with those currently used in this country, and appearing among the A. I. E. E. standards. Furthermore, the Commission recognized the fundamental candle-power unit, which is maintained by the National Laboratories of Great Britain, France and the United States, as the "International Candle." The Commission also appointed subcommittees on "Heterochromatic Photometry," on "Definitions and Symbols," on "Lighting in Factories and Schools," and on "Automobile Head Lights."

It is proposed that the next meeting of the Commission shall be held, (assuming that conditions are favorable), in this country, in 1924. Dr. E. P. Hyde of the U. S. National Committee was elected President of the International Commission.

At the meeting of the U. S. National Committee, held in November, 1921, C. H. Sharp was elected Chairman of the U. S. National Committee, and Howard Lyon was elected its Secretary.

Code of Principles of Professional Conduct.—Two cases of alleged breaches of our code by members of the Institute have been presented to the committee during the past year. In one of these cases, involving the presentation of false information, the committee found the charge warranted and recommended that the member's resignation, presented in the interim, be accepted by the Board. In the other case, involving the unauthorized use of the name of the Institute for advertising purposes in a printed document, the committee recommended severe censure and the withdrawal of the document in question.

Both of these recommendations were accepted and acted upon by the Board.

At its meeting on February 16, the committee recommended the policy of publishing the findings of the committee in the Institute JOURNAL, each case to be presented as an example of the interpretation of the code, and without names. After referring this matter to the legal counsel of the Institute, the recommendation was approved by the Board, and a brief statement of the cases above mentioned was prepared and published.

During the past two years, a committee of the American Society of Mechanical Engineers, cooperating with representatives of the other societies, has been preparing a joint code of ethics. After careful consideration of this code, your committee has recommended that the Institute adhere to its present code, rather than adopt the proposed joint code. It is the opinion of the committee that the existing code of the Institute is more complete and explicit than the proposed joint code, and more unquestionable in its interpretation. This recommendation was also approved by the Board of Directors.

Committee on Safety Codes.—The Committee has cooperated with the Electrical Committee of the National Fire Protection Assoc. by having representatives on its subcommittee on Industrial Applications, and by the suggestion of certain ways in which the work of that Association can be more closely related to that of the A. I. E. E. The Institute is also represented by a member of this Committee in the Electrical Safety Conference Section Committee on Safety Code for Electric Power Control.

American Committee on Electrolysis.—The Institute's representatives on the American Committee on Electrolysis have attended all meetings of the Committee held during the year 1921, the last one of which occurred on May 3, 1921. The great interest taken in the work was evidenced by the fact that all of the organizations constituting the committee were represented, there being present 24 out of the 27 representatives.

At this meeting the reports of the various subcommittees were thoroughly discussed and unanimously adopted. These reports were then referred to an editing committee and, together with an introduction by the Chairman, published about October 21, 1921, as the Second Report of the Committee. They are being distributed through the A. I. E. E. in the same manner that the First Report was handled.

While the main committee has been inactive since the May 3, 1921 meeting, the work of the Research subcommittee is going actively forward.

Board of Examiners.—The Board of Examiners during the year held eleven meetings, averaging about three hours each. It considered and referred to the Board of Directors a total of 3420 applications for admission or transfer to the higher grades. This is a decrease of about 21% from the record figures of last year and is undoubtedly accounted for by the industrial depression from which the country suffered during the year.

During the early part of the year a code of practise was drawn up by the Board giving the consensus of opinion on the various types of doubtful cases which arise. This code was adopted by the Examiners as a guide for future decisions.

APPLICATIONS FOR ADMISSION

Recommended for grade of Associate......	1662	
Not recommended......................	4	1666
Recommended for grade of Member........	111	
Not recommended for admission to this grade.........................	46	157
Recommended for grade of Fellow..........	1	
Not recommended for admission to this grade.........................	5	6
Recommended for enrolment as Students...	1390	
Not recommended for enrolment...........	1	1391

APPLICATIONS FOR TRANSFER

Recommended for grade of Member.........	131	
Not recommended for transfer to this grade	38	169
Recommended for grade of Fellow..........	21	
Not recommended for transfer to this grade	10	31
Total number of applications considered....		3420
Applications reconsidered.................		4
Total..................................		3424

Membership.—The results of the Membership Committee's efforts this year should be considered excellent in view of the period of industrial depression through what the country has been passing. The larger Sections of the Institute located in manufacturing centers felt the effect of business curtailment most sharply, twelve of the smaller Sections on the other hand exceeded last year's figures.

The total applications received were 1748 as compared with 2442 last year and 1596 the year before. The accompanying table shows the changes in membership in detail.

	Honorary Member	Fellow	Member	Associate	Total
Membership, April 30, 1921..	6	541	1,903	10,765	13,215
Additions:					
Transferred..............		23	146		
New Member Qualified....	1	1	114	1,646	
Reinstated..............		2	9	30	
Deductions:					
Died.....................	1	5	11	45	
Resigned.................		3	20	187	
Transferred..............			14	155	
Dropped..................		1	30	461	
Membership, April 30, 1922..	6	558	2,097	11,602	14,263

Net increase in Membership during the year.......................... 1048

Deaths.—The following deaths have occurred during the year.

Honorary Member: E. A. Budde.

Fellows: Wilson L. Campbell, Warren H. Fiske, R. T. E. Lozier, L. S. Randolph, Edward B. Rosa.

Members: Francis B. Crocker, Charles R. Cross, Leo Daft, W. F. Doherty, Roland S. Feud, Alexander M. Gray, George G. Grower, Peter C. Hewitt, Llewelyn Owen, Richard Pfund, James A. Walton.

Associates: Joel E. Anderson, Walter E. Aymonds, Milton P. Baker, William E. Baker, James H. Becker, Rayner M. Bedell, Joseph E. Biggs, Winthrop G. Bushnell, Dean B. Cobb, Harry L. Darrah, S. I. Felder, Wm. Lee Fitzpatrick, Clark W. Francy, Alonzo Gartley, Frank T. Gash, C. M. Gear, Carl F. Grimm, Henry Harvie, Percy C. Henry, Earl S. James, A. Pinto Joseph, Shuso Kawado, Edwin W. Kelly, Frederick A. Keyes, Joseph F. Krause, Walter A. Leason, W. W. Lighthipe, Myron Manwaring, Robert McKay, Ferdinand C. Miller, Edward S. Morrell, Fred C. Muench, Charles A. Rohr, Earl E. Sayre, Leon H. Scherck, Albert C. Schweizer, Harry M. Steven, Albert Taylor, Willis H. Trenner, Alfred R. Van Horn, Arthur S. Wheeler, B. D. Wilber, J. F. Wilson, Noble A. Wolfe, Roy C. Zoll.

Total deaths, 62.

Employment Service.—The employment service which has been maintained for many years at Institute headquarters and which during the latter part of 1918 was coordinated with the similar service of the other Founder Societies, was transferred to the auspices of the newly organized American Engineering Council on January 1, 1921 upon the recommendation of the secretaries, and the Joint Finance Committee, of the four Founder Societies.

In addition to a direct service, the Bureau prepares an engineering service bulletin which is published each month in the Institute JOURNAL and it has served to place many members in positions of responsibility, both in this country and abroad. The bulletin is subdivided into two parts: one containing announcements of vacancies; and the other containing lists of men available, with condensed records of their experience. All announcements are published without charge either to the employers or to the members of the Institute seeking positions.

With a view to increasing the scope and value of the Bureau a volunteer committee, composed of engineers registered with the bureau, was organized early in the summer of 1921 and has been at work almost continuously since that date systematically canvasing employers of engineers in and around New York, largely through the medium of personal calls, calling attention of these employers to the facilities offered by the bureau. This work has been productive of very satisfactory results and is also being undertaken in other cities.

Federated American Engineering Societies.—During the past year meetings of the Executive Board of American Engineering Council have been held as follows: April 16, 1921, Philadelphia; September 30, 1921, Washington; January 4 and 6, 1922, Washington; March 10, 1922, Chicago. In addition to this the first annual meeting of American Engineering Council was held January 5-6 at Washington.

The headquarters of the organization were early in 1921 transferred from New York to Washington and it is believed that one result of the first year's activities, as shown there, is a distinct field of usefulness for the organization; that distinct progress in securing the support and earning the confidence of the engineers of the country has been made, and the prestige of the profession—both in Government and in industrial circles—has been enhanced. It would seem that the Institute pursued a wise course in participating in the creation of this organization and of giving it whole hearted support.

Detailed accounts of the activities of American Engineering Council and of its Committees have been published throughout the year in the JOURNAL and will not be recapitulated here.

At the annual review of membership, the Institute became entitled to two additional members on American Engineering Council and to an additional member on the Executive Board. President McClellan, Past-Presidents Scott, Stillwell and Townley retain their seats on the Executive Board, the additional members being Messrs. Finney and Morehouse. In the Committee appointments, Professor Charles F. Scott has become Chairman of the Committee on Constitution and By-Laws, Mr. L. B. Stillwell, remains on the Committee on Public Affairs and Mr. Calvert Townley on the Committee on Finance.

United Engineering Society.—This Society performs for the national societies of Civil, Mining, Mechanical and Electrical Engineers, certain specific acts which are governed by contracts; the primary function of the United Society being to hold in trust and to administer for these societies the Engineering Societies Building, in which the headquarters of the National societies are located.

Extracts from the annual financial report of the United Engineering Society were published in the March 1922 JOURNAL.

Engineering Societies Library.—The library of the Institute is combined with the libraries of the national societies of Civil, Mining and Mechanical Engineers, administered as the "Engineering Societies Library" under the direction of the Library Board of the United Engineering Society; this board is composed of representatives of each of the four societies referred to above.

In order to place the facilities of the library at the disposal of persons residing at a distance from New York, a Library Service Bureau has been established, and a staff of expert searchers and translators is employed to cover almost any engineering topic, in the following manner: abstracting, translating, bibliographing, statistical searches and reports, searches for patent purposes, copying, preparing reference cards, etc.

An abstract of the annual report of the Engineering Societies Library covering the calendar year 1921 was published in the March 1922 JOURNAL.

Engineering Foundation.—Engineering Foundation is a trust fund established in 1914 by Ambrose Swasey, of Cleveland, Ohio, by gifts to United Engineering Society as a nucleus of a large endowment "for the furtherance of research in science and in engineering, or for the advancement in any other manner of the profession of engineering and the good of mankind." It is administered by the Engineering Foundation Board upon which the Institute and other national engineering societies are represented. The Board is a Department of United Engineering Society.

An abstract of the annual report of the Engineering Foundation for the seventh year, was published in the March 1922 JOURNAL.

Representatives.—The Institute has continued its representation upon various national committees and other local and national bodies with which it has been affiliated in past years, and has appointed representatives upon a number of new Sectional Committees of American Engineering Standards Committee. A complete list of representatives is published frequently in the JOURNAL.

Edison Medal.—The Edison Medal for 1921 which was awarded to Cummings C. Chesney "For Early Developments in Alternating-Current Transmission" was presented to Mr. Chesney with appropriate ceremonies at an evening session of the Midwinter Convention, February 16, 1922.

John Fritz Medal.—The John Fritz Medal Board of Award, which is composed of representatives of the national societies of Civil, Mining, Mechanical and Electrical Engineers, awarded the 1922 medal to Charles Eugene Schneider "for achievement in metallurgy of iron and steel; for development of ordnance, especially the 75 mm. gun, and for notable patriotic contribution to the winning of the war."

Visit of American Engineers to England and France.—A delegation of American engineers representing the four societies of Civil, Mining, Mechanical and Electrical Engineers visited England and France during the summer of 1921. The purpose of this visit was the presentation of the John Fritz Medal to Sir Robert Hadfield in London and Charles Eugene Schneider in Paris. The Institute was represented by

Dr. F. B. Jewett, Dr. A. E. Kennelly and Major General George O. Squier. The reception of the American delegation in both London and Paris was the occasion in both instances for the gathering of an unprecedented number of distinguished engineers and the keynote of most of the speeches was the international character of engineering, and the importance of developing intimate relations between the members of the professions of the different countries, leading to a better understanding between the nations.

Honorary Membership.—Marshal Foch was made an honorary member of the four national societies of Civil, Mining and Metallurgical, Mechanical and Electrical Engineers with impressive ceremonies on the afternoon of December 13, 1921 at the Engineering Societies Building, New York.

Finance Committee.—During the year the committee has held monthly meetings, has passed upon the expenditures of the Institute for various purposes, and otherwise performed the duties prescribed for it in the Constitution and By-laws.

Haskins and Sells, certified public accountants, have audited the books, and their report follows:

ATLANTA
BALTIMORE
BOSTON
BUFFALO
CHICAGO
CINCINNATI
CLEVELAND
DALLAS
DENVER
DETROIT
KANSAS CITY
LOS ANGELES
MINNEAPOLIS
NEWARK
NEW ORLEANS

HASKINS & SELLS
CERTIFIED PUBLIC ACCOUNTANTS
37 WEST 39TH STREET
NEW YORK

NEW YORK
PHILADELPHIA
PITTSBURGH
PORTLAND
SAINT LOUIS
SALT LAKE CITY
SAN FRANCISCO
SEATTLE
TULSA
WATERTOWN

HAVANA
LONDON
PARIS
SHANGHAI

May 15,1922.

American Institute of Electrical Engineers,
33 West 39th Street,
New York.

Dear Sirs:

Pursuant to engagement, we have audited your books and accounts for the year ended April 30, 1922, and submit herewith our certificate and the following described exhibits:

Exhibit "A"—General Balance Sheet, April 30, 1922.

Exhibit "B"—Summary of Income and Profit & Loss for the Year ended April 30, 1922.

Yours truly,

HASKINS & SELLS

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

CERTIFICATE OF AUDIT

We have audited the books and accounts of the American Institute of Electrical Engineers for the year ended April 30, 1922, and

WE HEREBY CERTIFY that the accompanying General Balance Sheet properly exhibits the financial condition of the Institute at April 30, 1922, that the Summary of Income and Profit & Loss for the year ended that date is correct, and that the books of the Institute are in agreement therewith.

HASKINS & SELLS

NEW YORK,
May 15, 1922.

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

Exhibit A.

General Balance Sheet, April 30, 1922

ASSETS

Real Estate:			
One-Fourth Interest in United Engineering Society's Land, Building and Building Equipment, 25 to 33 West 39th Street, (Depreciation carried on Books of United Engineering Society)			$489,785.17
Equipment:			
Library—Volumes and Fixtures		$40,374.43	
Works of Art, Paintings, etc.		3,001.35	
Office Furniture and Fixtures	$14,558.20		
Less Reserve for Depreciation	9,788.28	4,769.92	
Total Equipment			48,145.70
Working Assets:			
"Transactions," etc.		$6,730.50	
Paper and Cover Paper		2,008.17	
Paper for Volume 40		874.84	
Badges		1,769.48	
Total Working Assets			11,382.99
Current Assets:			
Cash		$398.09	
Notes Receivable—Advertisers		253.75	
Accounts Receivable:			
Members—For Dues		13,784.24	
Advertisers		2,765.56	
Miscellaneous		1,012.43	
Accrued Interest on Investments		109.38	
Accrued Interest on Bank Balances		183.09	
Total Current Assets			18,506.54
Funds:			
Reserve Capital Fund:			
City of Wilmington, Delaware, 4½% Bonds, 1934, par Value $15,000.00	$15,625.63		
United States Third Liberty Loan 4¼% Bonds, par Value, $10,000.00	10,000.00	$25,625.63	
Life Membership Fund:			
Cash	$1,438.67		
Chicago, Burlington & Quincy Railroad Company 4% Bonds, 1958, par value, $5,000.00	4,868.75		
Accrued Interest	33.33	6,340.75	
International Electrical Congress of St. Louis—Library fund:			
Cash	$275.95		
New York City 4½% Bonds, 1957, par value $2,000.00	2,223.19		
New York Telephone Company 4½% Bond, 1939, par value $1,000.00	878.75		
Accrued Interest	67.50	3,445.39	
Mailloux Fund:			
Cash	$90.00		
New York Telephone Company 4½% Bond, 1939, par value $1,000.00	1,000.00		
Accrued Interest	22.50	1,112.50	
Midwinter Convention Fund—Cash		242.87	
Total Funds			36,767.14
Total			$604,587.54

LIABILITIES

Current Liabilities:		
Accounts Payable—Subject to Approval by the Finance Committee	$11,395.41	
Due to United Engineering Society on Account of Building Addition, Including Accrued Interest	2,542.19	
Dues Received in Advance	2,754.91	
Entrance Fees and Dues Advanced by Applicants for Membership	357.50	
Subscriptions for "Transactions" Received in Advance	3,026.00	
Total Current Liabilities		$20,076.01
Fund Reserves:		
Reserve Capital Fund	$25,625.63	
Life Membership Fund	6,340.75	
International Electrical Congress of St. Louis—Library Fund	3,445.39	
Mailloux Fund	1,112.50	
Midwinter Convention Fund	242.87	
Total Fund Reserves		36,767.14
Surplus: Per Exhibit "B"		547,744.39
Total		$604,587.54

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

SUMMARY OF INCOME AND PROFIT & LOSS FOR THE YEAR ENDED APRIL 30, 1922.

EXHIBIT B.

INCOME:			
Entrance fees		$9,719.25	
Dues		*152,590.11	
Student's Dues		10,127.00	
Transfer Fees		1,732.50	
Advertising		54,820.60	
Subscriptions		4,907.74	
Sales of "Transactions," etc.		10,199.67	
Badges Sold	$5,172.75		
Less Cost	4,774.30	398.45	
Interest on Securities in Reserve Capital Fund		1,100.00	
Interest on Bank Balances		842.65	
Interest on Notes Receivable		32.90	
Total			$246,470.87
EXPENSES:			
Publications:			
Journal	$77,288.92		
Transactions	28,830.77		
Year Book	5,026.78	$111,146.47	
Meetings		7,903.32	
Administrative Expenses		42,974.76	
Sections Committee		24,596.76	
Membership Committee		6,611.21	
Standards Committee		103.36	
Finance Committee		150.00	
Code Committee		60.00	
International Electrotechnical Commission		872.42	
International Illumination Commission		300.00	
Interest on United Engineering Society Building Account		182.79	
President's Special Appropriation		588.96	
Honorary Secretary		4,000.00	
American Engineering Standards Committee		1,600.10	
John Fritz Medal Award		57.14	
Engineering Societies Library:			
Maintenance	$5,500.00		
Recataloging	2,500.00	8,000.00	
United Engineering Society Assessment		4,860.00	
Federated American Engineering Societies		17,927.50	
Forward		$231,934.79	$246,470.87

*Includes $66,075.00 representing the Institute's estimate of members' dues applicable to subscriptions for the JOURNAL.

TOTAL INCOME—(Forward)		$246,470.87
EXPENSES—(Forward)	$231,934.79	
Interest on Loans Payable	20.00	
Total		231,954.79
NET INCOME		$14,516.08
PROFIT & LOSS CREDITS:		
Adjustment of Institute's One-Fourth Interest in United Engineering Society's Real Estate	$2,992.38	
Adjustment of Inventory of Furniture and Fixtures, April 30, 1922	420.98	
Adjustment of Inventory of Library Volumes and Fixtures, April 30, 1922	169.44	
Total		3,582.80
GROSS SURPLUS FOR THE YEAR		$18,098.88
PROFIT & LOSS CHARGES:		
Uncollectible Dues Written Off	$4,317.47	
Adjustment of Inventory of Transactions, etc., April 30, 1922	6,176.00	
Provision for Depreciation of Furniture and Fixtures	424.81	
Total		10,918.28
SURPLUS FOR THE YEAR		$7,180.60
SURPLUS, MAY 1, 1921	$566,241.56	
Less Transferred to Capital Fund Reserve in Accordance with Resolution of Board of Directors	25,677.77	540,563.79
SURPLUS, APRIL 30, 1922		$547,744.39

AMERICAN INSTITUTE OF ELECTRICAL ENGINEERS

STATEMENT OF CASH RECEIPTS AND DISBURSEMENTS FOR DESIGNATED PURPOSES, FOR THE YEAR ENDED APRIL 30, 1922.

EXHIBIT C.

RECEIPTS:	
Life Membership Fund	$261.26
International Electrical Congress of St. Louis Library Fund—Interest and Royalties	139.40
Mailloux Fund—Interest	45.00
Midwinter Convention Fund—Interest	13.00
Total	$458.66
DISBURSEMENTS:	
Life Membership Fund	$261.86
International Electrical Congress of St. Louis Library Fund	281.01
Mailloux Fund	186.60
Midwinter Convention Fund	232.39
Total	$961.86

RECEIPTS AND DISBURSEMENTS PER MEMBER.

During each fiscal year for the past seven years.

Year ending April 30	1916	1917	1918	1919	1920	1921	1922
Membership, April 30, each year	8212	8710	9282	10252	11345	13215	14263
Receipts per Member	$13.62	$13.30	$13.17	$13.18	$15.01	$17.87	$17.26
Disbursements per Member	13.74	12.75	11.99	12.92	15.62	18.90	16.77
Credit Balance per Member	*$.12	$.55	$1.18	$.26	*$.61	*$1.03	$.49

*Deficit.

Respectfully submitted for the Board of Directors.

F. L. HUTCHINSON, *Secretary.*

New York, May 19, 1922.

Officers of A. I. E. E. 1921-1922

PRESIDENT.

WILLIAM McCLELLAN

JUNIOR PAST-PRESIDENTS

CALVERT TOWNLEY
A. W. BERRESFORD

VICE-PRESIDENTS

W. A. HALL
W. A. DEL MAR
J. C. PARKER
H. W. EALES
O. B. COLDWELL
N. W. STORER
C. G. ADSIT
F. W. SPRINGER
ROBERT SIBLEY
F. R. EWART

MANAGERS

WALTER I. SLICHTER
G. FACCIOLI
FRANK D. NEWBURY
HAROLD B. SMITH
JAMES F. LINCOLN
E. B. CRAFT
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